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THE JOURNAL OF GEOLOGY

January 1946

AN EXAMPLE OF THE DEVELOPMENT OF CLEAVAGES

JOHN G. BROUGHTON
New York State Museum, Albany

ABSTRACT

An attempt is made to follow the development of secondary structures in a slate, the Martinsburg formation in Warren County, New Jersey. In part of the area discussed, the structures are of the type common in slate regions with overturned folds, axial-plane flow cleavage, and the development of grain. Grain is believed to result from stretching of quartz grains in *a* rather than from tension normal to *ac* during elongation of the fold axis. Fabric analysis emphasizes the importance of elongation in *a*.

In the southern portion of the area described, other structures have been superimposed as a result of the movement of a thrust fault. The bedding is refolded, the flow cleavage is folded, and fracture cleavage parallels the axial planes. Closer to the thrust, antithetic rotation of the slate along the fracture cleavage has almost destroyed all evidence of the earlier flow cleavage and has caused the fracture cleavage itself closely to approximate flow cleavage in microscopic and megascopic appearance.

INTRODUCTION

The preservation of minute secondary structures is more nearly complete in slates than in almost any other rock. This is especially well illustrated by the highly deformed Ordovician slate belt running from northern Pennsylvania into New Jersey. C. H. Behre, Jr.,[1] has shown that in this area the many megascopic structures make structural interpretation far more complete than is usually possible. This paper summarizes an investigation of the New Jersey slates made by the writer in 1938–40.

GENERAL DESCRIPTION

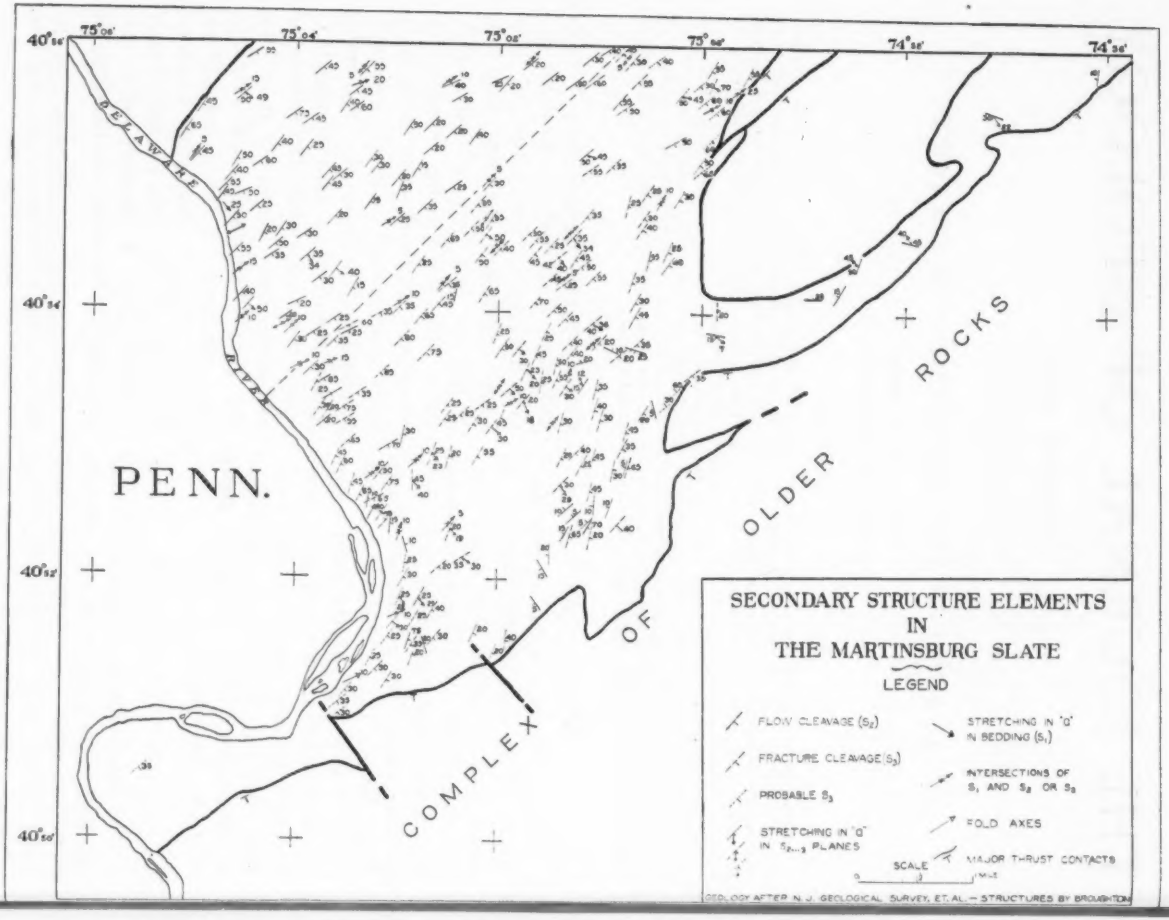
The Martinsburg formation, of middle and upper Ordovician age, extends northeast across New Jersey from latitude 75° 05′ west to latitude 74° 35′ west, in a belt approximately 7 miles wide. For about two-thirds of that distance a septum of older Kittatinny limestone (Allentown and Beekmantown) divides the belt into two parts. Elsewhere the Martinsburg formation is found only in small areas which have been downfaulted between pre-Cambrian ridges. The region discussed in this paper comprises an area of about 33 square miles south of the limestone band and immediately across the river from the Pennsylvania slate belt (Fig. 1). The thickness of the Martinsburg, where estimated along the Delaware River, ranges from 3000 to 11,000 feet.[2,3]

Three planes of reference can be distinguished in the slates; the bedding, the

[1] "Slate in Pennsylvania," *Pa. Geol. Surv. Bull. M16* (4th ser., 1933).

[2] G. W. Stose, "Uncomformity at the Base of the Silurian in Southeastern Pennsylvania," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930) p. 634.

[3] P. 137 of ftn. 1.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DELAWARE
RIVER
PENN.
OLDER ROCKS
COMPLEX
SECONDARY STRUCTURE ELEMENTS
IN
THE MARTINSBURG SLATE
LEGEND
FLOW CLEAVAGE (S_2)
FRACTURE CLEAVAGE (S_3)
PROBABLE S_3
STRETCHING IN 'Q' IN S_{2-3} PLANES
STRETCHING IN 'Q' IN BEDDING (S_1)
INTERSECTIONS OF S_1 AND S_2 OR S_3
FOLD AXES
MAJOR THRUST CONTACTS
SCALE
GEOLOGY AFTER N. J. GEOLOGICAL SURVEY, ET AL. — STRUCTURES BY BROUGHTON

flow cleavage, and the fracture cleavage. They will be referred to as S_1, S_2, and S_3, respectively. All structures are described by reference to a triaxial coordinate system. Axis *a* represents the direction of transport, whether it is in a bedding plane, a cleavage, or elsewhere. Axis *b* is normal to it and parallels the fold axes. Axis *c* is normal to the *ab* plane.

Compass directions are referred to a circle of 360° rather than to four quadrants of 90° each.

STRUCTURE

BEDDING (S_1)

The formation has been subdivided lithologically by Behre[4]

> into a lower, a middle, and an upper part. The lower part is characteristically a banded clay slate, though there are also thin sandstone beds. The middle member contains sandy beds as its most typical facies, though some truly slaty beds are also found in it. The uppermost member is banded like the lower, but there is less sand and the undivided beds are much thicker. The differences between these subdivisions are relative, and in areal mapping the line between them is drawn with difficulty.

A difference of opinion exists as to the actual occurrence of this upper member. Stose[5] believes that it is simply the lower member repeated by folding. Since the question can have little or no bearing on the subject of the slate structures, it will not be discussed further here.

Numerous thin sections of the slate were studied under the microscope. They show that the most common facies of the slate are (1) sericitic slate with carbonaceous matter and a small percentage of quartz and (2) beds made up predominantly of angular quartz grains. The latter beds are seldom more than 2 or 3 feet thick. A very noticeable structure of these sandy beds is an intricate folding, completely contained within the bed and emphasized by contorted films of black, probably carbonaceous, material. These folds seem to bear no regular relation to the axes of deformation and show no parallelism among themselves. It was not possible to collect a satisfactory specimen for petrofabric analysis. W. H. Twenhofel[6] assigns structures of similar appearance to deformation during sedimentation. W. H. Bucher (personal correspondence, 1944) calls this "interstratal flow," differential movement between beds connected with unequal compaction of layers of different mobility.

Carbonate lenses occur locally in the slate. They are very minor features stratigraphically but are important structurally and therefore are discussed in the sections on folds and fold axes.

FOLDS AND FOLD AXES

Throughout the area the bedding has been folded and overturned to the northwest. Behre's areal map (1933, Pl. 24) seems to indicate that these small folds are only minor features. He shows the entire slate belt between the overthrust contact on the south and the limestone band on the north as one major syncline. The whole area can therefore be thought of as a synclinorium.

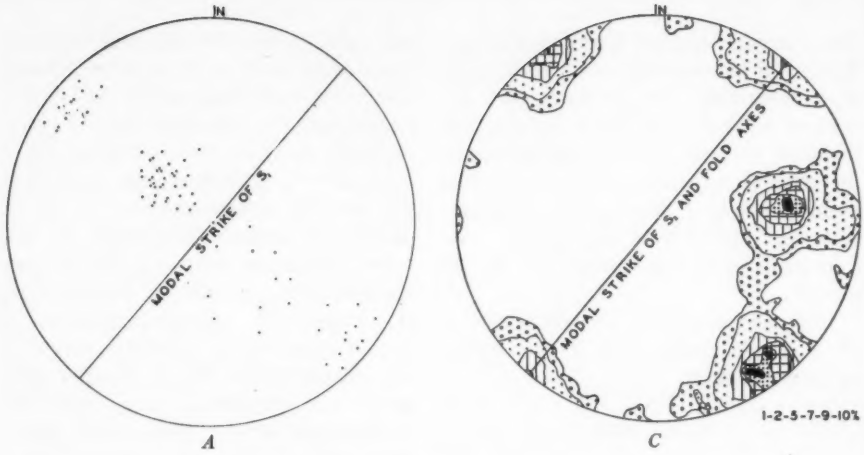
The fold axes most commonly pitch 5°–20° to the northeast. At a few localities they are horizontal, and rarely pitch to the southwest.

In the highway cut along the Delaware River between Columbia and Delaware, New Jersey, the slate is well exposed. Figure 2, *A*, is a diagram of the poles of bedding planes measured in this

[4] P. 136 of ftn. 1.

[5] Ftn. 2.

[6] *Principles of Sedimentation* (New York: McGraw-Hill Book Co., Inc., 1939), p. 529.



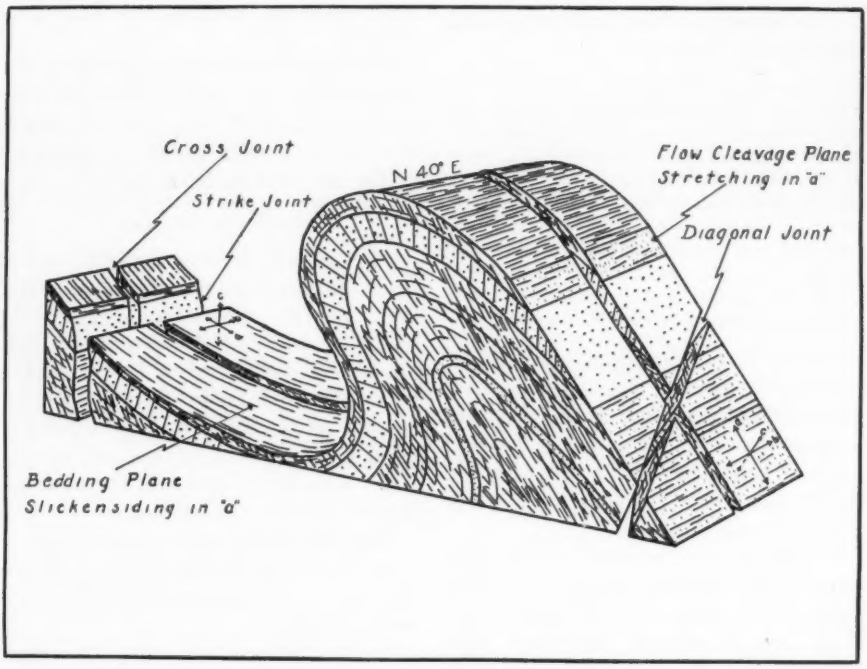


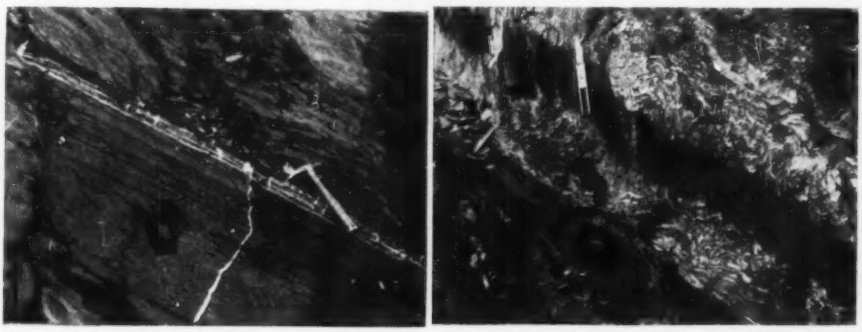
FIG. 2.—Diagrammatic analysis of slate structures (Columbia-Delaware section in northern or "normal" area). *A:* Seventy-five poles of bedding planes. *B:* Schematic diagram of major structural elements. *C:* Two hundred joint poles.

section, projected on a horizontal plane. The most common (modal) strike of the bedding derived from these data is 45°, and the dip is 60°–70° southeast. The axes are horizontal or dip very gently to the northeast. The vertical girdle of points, which passes through the center of the diagram, indicates that the fold axes are ± horizontal. The concentration of points just northwest of the strike line indicates the predominance of overturning, with the gently dipping southeast limbs exposed over a greater area.

Prior to the development of cleavages, all movements resulting from folding took place along the bedding planes. This movement was in the direction fixed by the intersection of the *ac* plane and the bedding, i.e., in the *a* direction.

The most noticeable result of the folding in the sandy beds is thickening at crests and at troughs of folds. Less common is stretching of a competent horizon on the long limb of a fold so that it becomes attenuated and in some cases has broken across the bed to form a blunt lens. This is an extreme result of stretching in *a* and is not to be confused with boudinage structure,[7, 8] which has no recognizable strike and is supposedly dependent for its distinctive barrel-like cross section on both tension and compression.

As mentioned by Behre,[9] horizons of almost pure calcite up to 3 or 4 inches thick are common and are most noticeable on the southeast limbs of the folds. They have evidently been planes of movement, as they are deeply slickensided in the *a* direction. At places these bedding slips break across at a low angle and become true thrust faults. Extensive movement has resulted in the development of wide ribbons with included angular slate fragments. Associated with the movement in *a*, minor tension joints in *bc* have been opened and then filled somewhat later with quartz (Fig. 3).



A *B*

FIG. 3.—*A: bc* tension joints have opened up across calcite horizon ("silver ribbon") and later have been filled with quartz. Columbia-Delaware section. *B:* Shear folding along flow cleavage plane in a wide calcite horizon.

The bedding is intersected by flow

[7] P. J. Holmquist, "On the Relations of the 'Boudinage Structure,'" *Geol. fören. i. Stockholm förhandl.*, Vol. LIII, Part II (1931), pp. 193–208.

[8] T. T. Quirke, "Boudinage and Unusual Structural Phenomenon," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1923), pp. 649–60.

[9] P. 148 of ftn. 1.

cleavage. Because the flow cleavage normally lies in the axial plane of the overturned folds, these intersections may, for all practical purposes, be regarded as parallel to the fold axes (*b*). The pitching of folds results in minor convergences and divergences of the two, but for small angles of pitch these differences are negligible.

South of the dashed line on the map renders its active role. From that time on, most movements will take place along the new *S* planes. The bedding is passive. A later stage of the folding illustrates this principle. Shear folding becomes the dominant type immediately upon formation of the cleavage planes. It results from minute movements along the cleavage planes and, in this region at least, simply accentuates the original

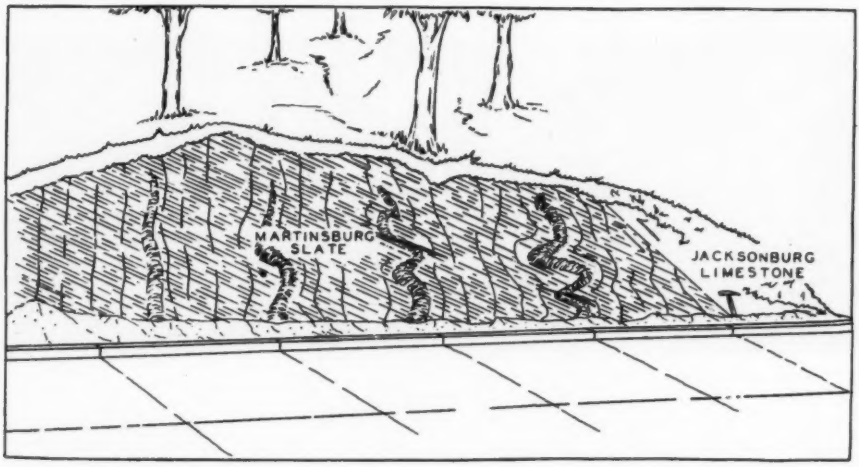


FIG. 4.—Aclinal folding. Sheared S_3 transects bedding and is folded with it. Black bars across folds represent quartz veins.

(Fig. 1), fracture cleavage is superimposed on flow cleavage. Here the intersections between bedding and fracture cleavage have been mapped as *b'*. As described below, when viewed in plan, the fracture cleavage cuts all earlier secondary *S* planes at a small angle. For this reason, the intersections with bedding are not so regular as in the northern area.

So far, all folding described has been flexure folding, in which the bedding is the important structural element. As soon as a cleavage develops which transects the bedding, the latter surfolds. Such structures have been described by E. Cloos.[10]

The latest stage of folding is in the vicinity of the major thrust fault (Fig. 1). The only locality where such folding may be observed is in the road cut on New Jersey Route No. 6 (Belvidere division). Here carbonate lenses have been contorted to a degree of intensity which is inversely proportional to their distance from the major overthrust contact. In this cut the thrust is represented by

[10] "The Application of Recent Structural Methods in the Crystalline Rocks of Maryland," *Md. Geol. Surv.*, Vol. XIII, Part I (1937), pp. 27–105.

Jacksonburg limy shale resting on the Martinsburg with 4–6 inches of gouge marking the contact. The bedding of the slate is generally vertical, with strong folding in the immediate vicinity of the lenses. The two lenses which have been most highly deformed are within 10 feet of the thrust; the last of the series is 125 feet from the contact and is the most gently folded. As shown in Figure 4, the cleavage (S_3) has been folded with the bedding. An apparently unavoidable conclusion is that this local folding has been caused by downward compression exerted by the overriding Jacksonburg on the vertical slate beds. It shows most strongly in the limy lenses because of their plastic character. Comparable structures, with similar interpretation, have been given the name "aclinal folds" by Edward Greenly.[11]

FLOW CLEAVAGE (S_2)

In order that a clear picture of the structural elements and their relations may be built up, it is important that flow and fracture cleavage be recognized as distinct features, although genetically there need not be, and probably is not, any difference between the two. By flow cleavage the author means a cleavage which has developed by rotation, flattening, and growth of mineral grains into approximate parallelism. The use of the term "fracture cleavage" is limited in this paper to a cleavage of the type defined by C. K. Leith[12] as "dependent for its existence on the development of incipient parallel fractures which by subsequent welding or cementation remain planes of weakness." In most cases the parallel fractures appear as minute faults associated with crenulations of the particular *S* plane which has been deformed. If this purely formal definition were followed, a cleavage plane would have its classification changed from flow cleavage to fracture cleavage as it passed from a shaly to a sandy bed (R. Balk[13]). A reasonable practice seems to be to use the name "flow cleavage" for the type that dominates at any particular exposure and therefore represents the highest degree of cleavage development at that exposure.

For the sake of clarity the slate area as mapped may be divided into a northern, or "normal," area and a southern area. In the first the structures are as described by Behre in Pennsylvania, while to the south they differ radically. The approximate line of demarcation between the two areas is marked by a broken line on Figure 1.

In the northern area, flow cleavage is the dominant secondary structure. Its attitude is extremely constant, striking 40° and dipping 45° southeast. This cleavage is a true axial-plane cleavage, which permeates the entire rock (Fig. 8, *A*). Bedding as a distinct plane of discontinuity has vanished and, except for the massive sandy beds, may be recognized only by color changes dependent on composition. The angle between the bedding and the cleavage may range between 0° and 90° (Fig. 5). As others have noted elsewhere, the angle at which flow cleavage crosses a bed is dependent on the competency of the bed and is always larger in the sandy members.

In the southern part of the slate belt, intricate structures are found involving

[11] The Geology of Anglesey," *Mem. Geol. Surv. Great Britain* (London, 1919), p. 190.

[12] "Rock Cleavage," *U.S. Geol. Surv. Bull. 239* (1905), p. 119.

[13] "Structural and Petrological Studies in Dutchess County, New York. I. Geological Structure of Sedimentary Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 706.

fracture cleavage, together with folded flow cleavage and refolded bedding. These structures are described below in more detail. However, it should be noted here that, south of the zone bounding the ordinary structures, flow cleavage becomes progressively more subordinate until, near the thrust contact, it has faded to a relict structure. In this belt, bedding and flow cleavage are most commonly parallel or subparallel.

Movement in the direction of $\dot{a}$ may be noted in the flow cleavage, as well as in the bedding. Evidence of this move-

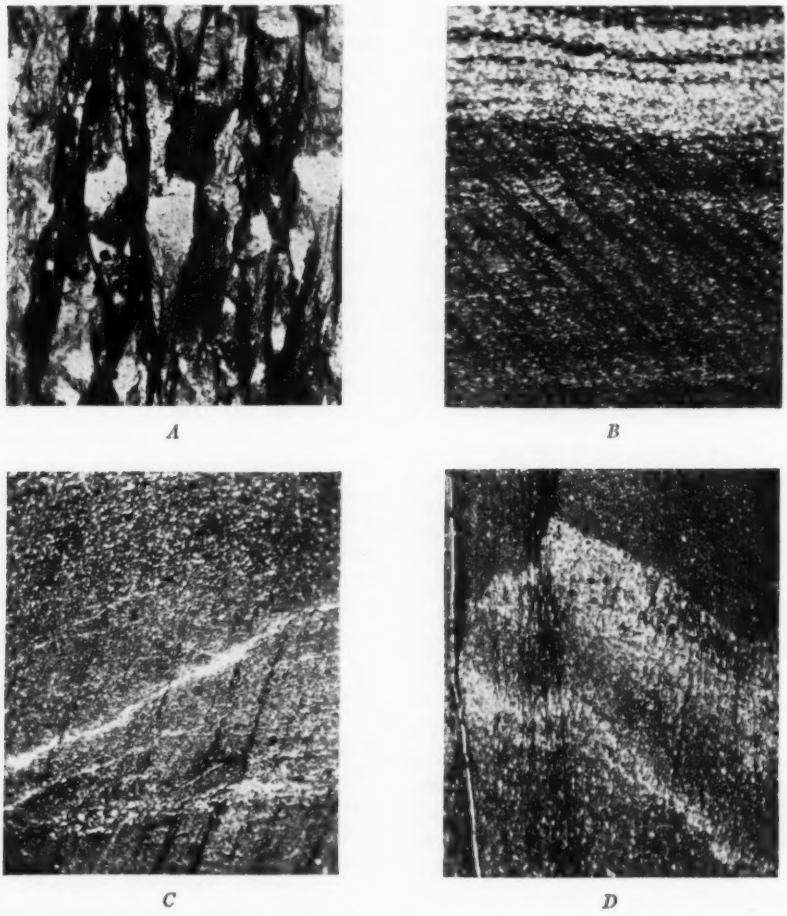


FIG. 5.—*A:* Quartz grains elongated in *a* of flow cleavage. Photomicrograph of Martinsburg slate near Pen Argyl, Pennsylvania, lent by Pennsylvania Geological Survey. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. Quartz grains elongated in *a* of flow cleavage. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C:* Fracture cleavage dipping steeply, flow cleavage gently, to the left. One-half mile southeast of Delaware (sp. 39–78). *D:* Same specimen as Fig. 7, *D*. Relict flow cleavage not visible (sp. 39–74).

ment can be seen very faintly in cleavage planes, expressed by a smearing-out of pyrite flakes into tiny parallel lenses. Other minerals show the same habit but cannot be identified. That this involves true stretching of the rock and not merely slickensiding is borne out by the microscopic evidence, which shows all quartz grains elongated in *a* (Fig. 5, *A*). This direction of elongation is included within the *ac* plane of potential weakness, generally known as the "grain" of slate. The elongation of quartz grains was developed during the formation of the flow cleavage, in the end stages of the folding process. The writer would question recent statements in the literature[14] that elongation of material in the axial plane of a fold normal to the direction of the fold axis is rare or questionable. Grain is a result of this quartz elongation (as well as that of other minerals). Interpretation of this pervasive structure as a tensional effect of the elongation of fold axes fails when it is recognized that the stretching in *a* developed at the same time as the h o l cleavage planes. The capacity of slate to be broken along these *ac* grain surfaces is directly dependent on the development of flow cleavage and the resulting mineral orientation.

FRACTURE CLEAVAGE (S_3)

In the belt of "normal" structures (northern area), fracture cleavage seems to be absent. The structure mapped by Behre as fracture (false) cleavage appears as small jointlike fissures, which give a wavy, crinkled effect to the flow cleavage (Fig. 7, *C*). In appearance it is similar to structures usually identified as fracture cleavage. It strikes parallel to the flow cleavage and dips 90° from it. Since it is found most commonly where thin shale beds are sheared between massive sandy horizons, Behre[15] ascribed its origin to such movement. It is now apparent that the origin is somewhat more complex (Fig. 6, *A* and *B*). The writer believes that the planes were formed originally as a result of tension parallel to *a* in the cleavage planes. Microscopic study shows that they are actually tiny gashes paralleling *bc* which peter out no more than 3 mm. from their surface of origin. The action of the bedding movement (Movement 1, Fig. 6, *B*) was secondary and resulted in slipping and flattening of the flow-cleavage planes (Movement 2, Fig. 6, *B*) by rotation between the massive sandstone layers. This caused an antithetic movement along the *bc* planes, which folded and dragged the flow-cleavage planes (Movement 3, Fig. 6, *B*). This structure has been noted only on the gently dipping southeastern limbs of the folds.

As one proceeds from north to south, one encounters in the vicinity of Delaware a fracture cleavage which is later than the bedding and the flow cleavage of the region as a whole. The dividing zone between the "normal" area and that in which this cleavage predominates parallels the regional strike and is so sharp that it has been represented on the inset map as a broken line. In a few localities this transition zone widens to about half a mile. From here on southward to the major overthrust, the dominant structure is a well-developed fracture cleavage which parallels the axial planes of flow-cleavage folds. This association indicates that it is genetically related to the folding. Locally, especially in the vicinity of quartz reefs, the contortion of S_2 is very strong (Fig. 8, *B*).

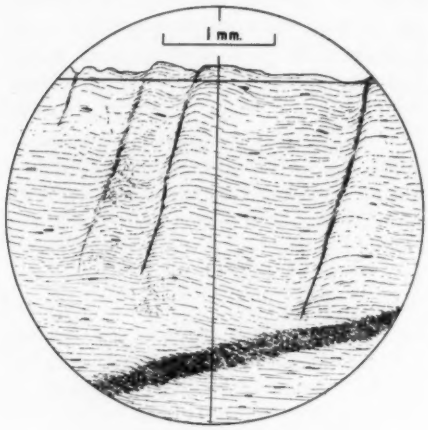
[14] E. B. Knopf, "Structural Petrology," *Geol. Soc. Amer. Mem. VI* (1938), p. 152.

[15] P. 36 of ftn. 1.

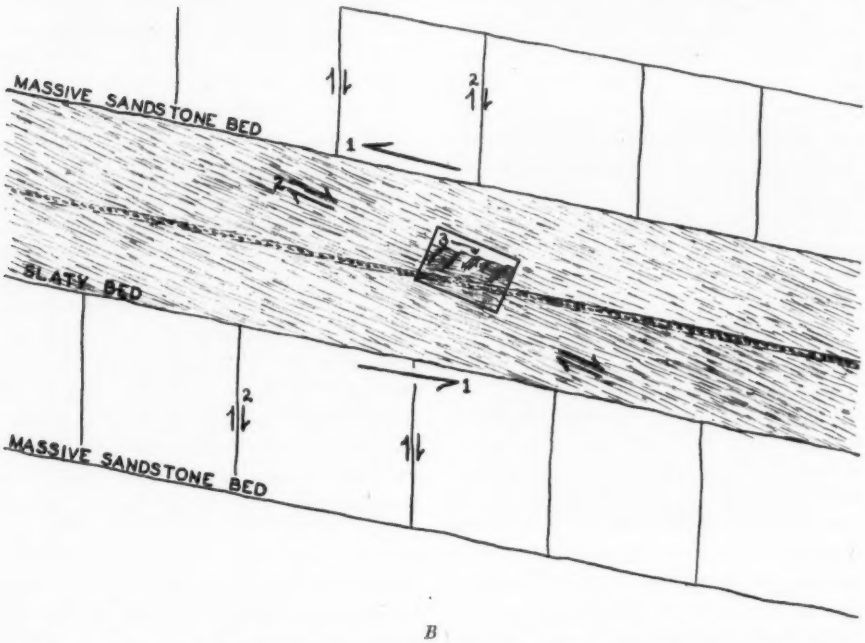
Elsewhere the flow cleavage is found at a small angle to, or parallel with, the bedding (Figs. 5, *B* and 7, *B*).

Relations of the three *S* planes to one another are particularly well exhibited in the Delaware, Lackawanna, and Western Railroad cut at Ramseysburg (Fig. 8, *B*) and a few hundred feet east of that cut on the road to Hope. At the latter exposure, numerous small, steep thrust faults have formed parallel to the fracture cleavage and then have broken through at anticlinal crests. Generally, where this late cleavage was formed, subsequent movement along it or along paralleling faults indicates antithetic rotation[16] to the northwest. Rotation of fracture-cleavage planes is indicated by drag of the earlier *S* planes and suggests flattening of S_3 as a result of continued pressure from the southeast.

[16] "Structure Elements of Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. XX (1936), p. 61.



A



B

FIG. 6.—*A:* Camera lucida drawing of rotated *bc* tension joints. *B:* Diagrammatic interpretation of structure shown in *A*. Rectangle gives location of thin section. Not to scale.

Slipping of the planes past one another has produced strong slickensiding on every fracture-cleavage surface. It is much more easily visible than the stretching along *a* in the flow cleavage, although it is not so pervasive. Consequently, it has had no effect on the internal structure, except possibly in a few localities where deformation was stronger.

Over most of the area these features of the fracture cleavage persist to the overthrust contact. However, at some localities marked on the map as "probable S_3," its appearance becomes so similar to normal flow cleavage that it was originally mapped as such (Fig. 8, *C*). Nevertheless, the writer has become convinced that it is the same fracture cleavage but that the slate has undergone intense deformation. As stated above, the original flow cleavage occurs at these exposures as a relict structure. This may be seen in the railroad cut at Manunka Chunk. Figure 7, *D*, is a good example of the mutual relations of the two cleavages

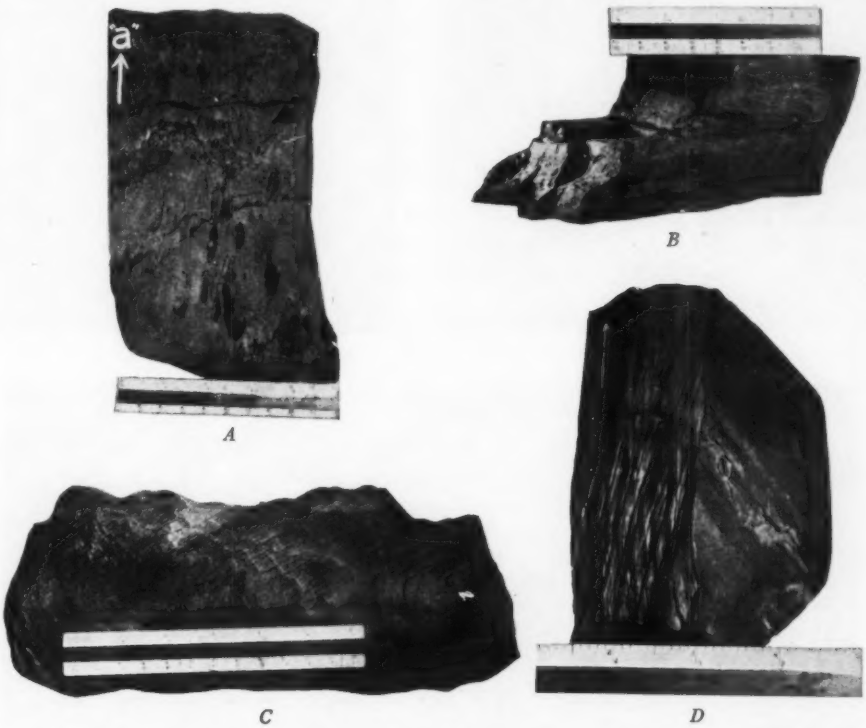
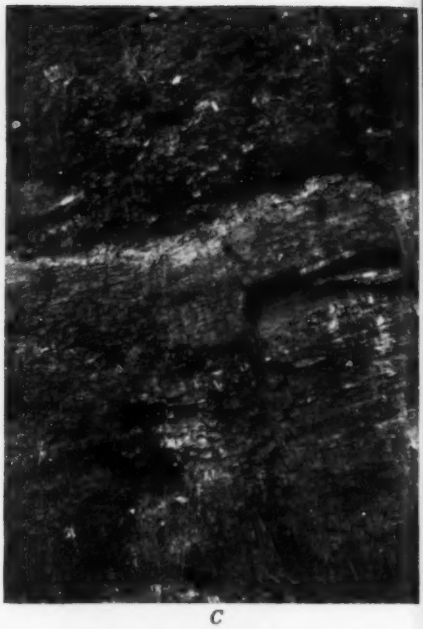


FIG. 7.—*A:* Fossils in Jacksonburg limestone pulled out by movement in *a* along bedding. Rock splits parallel to grain (*ac*). Near thrust contact, ¾ mile south of Swayse's Mills. *B:* Fracture cleavage dominant. Bedding and flow cleavage essentially parallel. One-quarter mile east of Ramseysburg on road to Hope (sp. 39–65). *C: bc* joints developed normal to *a* of flow cleavage. Columbia-Delaware section. *D:* Sheared fracture cleavage. Bedding dips away and to the right of the observer. Relict flow cleavage dips steeply to the left. Pennsylvania R.R. cut—Manunka Chunk (sp. 39–74).

A



C

B

FIG. 8.—*A:* Axial-plane flow cleavage. Columbia-Delaware section. *B:* Bedding roughly vertical. Flow cleavage gently dipping at left and extremely folded on right. Fracture cleavage parallels axial planes of flow-cleavage folds. D.L. & W.R.R. cut—Ramseysburg. *C:* Flow cleavage and bedding parallel and dipping gently to left (north). Fracture cleavage dominant and dipping steeply to right. Three hundred feet south of *B*.

and of the bedding. In thin section (Fig. 5, *D*), flow cleavage is not visible except upon insertion of the gypsum plate, when a faint structure may be seen crossing both fracture cleavage and bedding at an angle. The fracture-cleavage plane has lost its typical microscopic appearance and has developed into a structure which seems to be transitional between fracture cleavage and flow cleavage. The uniform elongation of quartz grains in S_2, observed farther north, has disappeared. The author has interpreted this phase as the result of continued and stronger pressures which have started to develop mineral reorientation and a resultant younger-generation flow cleavage along the fracture-cleavage planes.

Since the field work for this study was completed, a paper by W. J. Mead[17] has appeared, in which he sets up a threefold division for the secondary cleavages. Flow cleavage and fracture cleavage are two of the divisions. The third is "shear cleavage." Of this latter structure Mead says:

> This type of cleavage consists of roughly parallel, closely spaced surfaces of shear displacement on which platy minerals may have developed and into which they may have been dragged . . . . when the spacing is unusually close, shear cleavage may simulate and be easily confused with flow cleavage.

The writer believes that shear cleavage can be a transitional stage between flow and fracture cleavage. This is discussed below in more detail.

A genetic correlation of this regional fracture cleavage with the major overthrust, of which Jenny Jump Mountain is a part, seems to be an obvious conclusion. The main criteria on which this correlation is based are: (1) the bending of the fracture-cleavage strike opposite that part of the overthrust which seems to have advanced farthest, (2) the gradual increase in intensity of deformation toward the fault, and (3) the fact that the dip of the cleavage progressively flattens from north to south. All suggest the gradual building-up of stress from the southeast with antithetic rotation of the *S* planes, until, in the final stage, the weaker rocks were overridden by the older gneisses and limestones.

The sharp division between the two structure types in the slate is peculiar. The sudden change from fracture cleavage to flow cleavage northward suggests the possibility of a thrust entirely within the slate, although no such structure was observed. The author has refrained from adding another hypothetical fault to the many that have been postulated in the Appalachian province.

JOINTS

Three well-developed sets of joints cut the slate and its structures throughout the northern, or normal, part of the slate belt. Two hundred joints were measured along the Delaware River between Delaware and Columbia and their poles plotted on an equal-area net (Fig. 2, *C*). Comparison of this diagram with the block diagram (Fig. 2, *B*) illustrates their relation to the axes of deformation.

The submaximum in the first and third quadrants of Figure 2, *C*, represents vertical joints which are exactly at 90° to the strike of the fold axes. They are parallel to the grain of the *ac* direction in the rock and are thus in the proper geometric position for cross-joints. Grain of slate is such a pervasive plane of weakness that in any cut or excavation large vertical faces develop parallel to it. This is the sole joint direction

[17] "Folding Rocks Flowage and Foliate Structures," *Jour. Geol.*, Vol. XLVIII (1940), pp. 1007–11.

found constantly throughout the slate area, regardless of the cleavage type which exists. These joints appear most commonly where diagonal joints are rare. The roughhewn character and position of these cross-joints would seem to indicate that they are natural partings along the slate grain. The unevenness of the *ac* joints is explained by the fact that eventual breaking is not along one plane but along many roughly parallel planes, all including and being guided by the direction of quartz elongation (*a*). It is uncertain whether the actual fractures resulted from tension caused by elongation parallel to the *b* axis during folding or by continued pressure in a northwesterly direction after formation of grain. In the latter case, the *ac* joints might be thought of as incipient tear faults.[18]

The sharpest and smoothest joints are inclined to the *b* axis of folding (Fig. 2, *C*) and are probably shear joints. They are commonly coated with calcite films.

Strike joints (Fig. 2, *C*) have a very regular strike. However, it is common for the dip to swing from northwest to southeast or vice versa within a single joint. These surfaces are not so smooth as are the diagonal joints.

All three sets are best developed when their strike and dip are nearest the position indicated by the maximum on the diagrams.

FAULTS

The major fault affecting the slate belt is the thrust fault which bounds it on the south. Bayley and Kümmel[19] have interpreted it as a flat overthrust. The areal map of Northampton County, Pennsylvania,[20] shows no fault extending across the Delaware River into Pennsylvania.

Field evidence indicates that the thrust fault does exist, but it cannot be stated with certainty that it is a flat overthrust.

At the exposure on New Jersey Highway No. 6, from which the folded carbonate lenses are described, Jacksonburg limestone was found resting on Martinsburg slate with a foot or less of gouge between the two. This exposure is only $\frac{1}{2}$ mile east of Northampton County. The fault dips 40° southeast. On the evidence of this exposure, the author has drawn the fault line on his map $\frac{1}{4}$ mile north of where it appears on the New Jersey State Geological Map (1933).

On the southwest end of Jenny Jump Mountain, Kittatinny limestone was found below pre-Cambrian gneiss. The contact was not seen. However, the limestone has been completely silicified in a zone at least 5 feet thick and has been sheared into flat-lying (5°–15°) folia.

In a new highway cut, $\frac{1}{2}$ mile south of Swayze's Mills (2 miles southwest of Hope), the Jacksonburg cement rock is found in a highly contorted and shattered condition. Folding is intense, and stretching and lensing of sandy beds in *a* are common. A slab of rock taken from this locality shows fossils elongated parallel to *a* on the bedding planes (Fig. 7, *A*). The cement rock appears to be above the slate, but the actual contact was not seen. The author drew the fault line here farther north than it is drawn

[18] T. S. Lovering, "Field Evidence To Distinguish Overthrusting from Underthrusting," *Jour. Geol.*, Vol. XL (1932), p. 651.

[19] W. S. Bayley, H. B. Kümmel, and R. D. Salisbury, "Raritan Folio," *U.S. Geol. Surv. Folio, 191* (1914), p. 149.

[20] B. L. Miller and D. W. Fraser, "Northampton County, Pennsylvania," *Pa. Geol. Surv. Bull. C48* (4th ser., 1939), Pl. I.

on the state map, because of this exposure.

The attitude of fold axes around an outlier serves as a clue as to whether the rock mass is a true klippe or simply an anticlinal core. In the latter case, fold axes pitch outward in the surrounding rock. Not enough observations could be made at this locality. Nevertheless, as far as could be determined, fold axes in the slate pitch inward toward the limestone outlier. Since the limestone is the older rock, this synclinal structure indicates that there must be a fault separating the two.

Faults within the slate belt appear to be confined to renewed movement along zones of earlier fracture, such as the thrusting along fracture-cleavage planes near Ramseysburg. In places, faults have broken across the bedding planes as the dip changes near the crest of a fold. This is simply stronger movement of the same type that caused the common slickensiding in the *a* direction in the bedding planes. It is seen more often where flow cleavage and bedding are nearly parallel. In at least one case, rotation of the intermediate block has occurred between two slightly convergent bedding-plane faults. Feather joints may sometimes be noted branching off from the main plane of movement.

FABRIC

Fabric diagrams of typical specimens of the slate tend to corroborate the separation of the cleavage in the field.

Figure 9, *B*, is a diagram of two hundred quartz axes from a sandy layer in the slate of the "normal" area. This specimen (39–31) was collected along New Jersey Highway No. 8, $3\frac{1}{4}$ miles south of Columbia. The attitude of the flow-cleavage plane (S_2) has been indicated. There is no visible fracture cleavage. The concentric circles represent those circles passing through the theoretical quartz tectonite maximums.[21] There is some elongation of the individual quartz grains in *a* of the flow cleavage, but this is not so marked as in the more shaly layers. The quartz grains average 0.05 mm. in diameter.

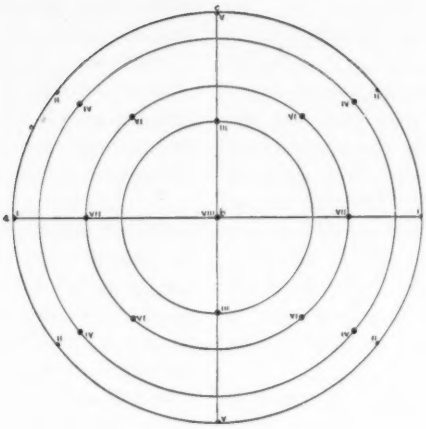
Coincidence of actual point maximums with those theoretically possible is the exception rather than the rule. However, rotation about *b* is indicated, inasmuch as all the more important maximums and submaximums fall on, or very near, some of the maximum circles. The maximum of 4 per cent at *a* is most easily identified.

It corresponds to Maximum I, which has been interpreted[22] as a result of quartz breaking into needles parallel to its *c* axis and orientation of the needles parallel to fabric axis *a*. A maximum of equal importance lies in the *ac* plane 56° ± from *a*. Lying, as it does, midway between the theoretical Maximums II and V (Fig. 9, *A*), its interpretation is questionable. There is no field evidence to support the hypothesis that it represents Maximum I of another cleavage plane. It will fall roughly on the VI circle if *a* is taken as an axis of rotation; but in this locality there is no evidence whatever to suggest that such was the case. Finally, it may be taken simply as a point maximum falling on the *ac* girdle I-II-V. Whatever the allocation, the author does not feel capable of giving an adequate interpretation.

Submaximums of 3 per cent each lie on the IV, VI, and III circles. The actual

[21] H. W. Fairbairn, *Structural Petrology of Deformed Rocks* (1942), p. 68.

[22] David Griggs and J. R. Bell, "Experiments Bearing on the Orientation of Quartz in Deformed Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 1743.



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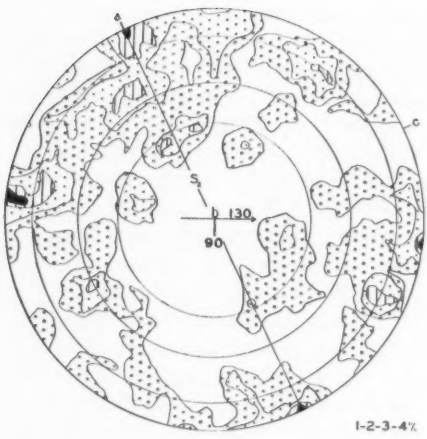

B

C

FIG. 9.—*A:* Theoretical quartz tectonite maxima after H. W. Fairbairn in *Structural Petrology of Deformed Rocks* (Cambridge, Mass.: Addison-Wesley, 1942). Drawing reproduced by permission of the author. *B:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–31. *C:* Fabric diagram with optic axes of 200 quartz grains in sp. 39–74.

and theoretical maximums coincide in only one case.

Figure 9, *C* (39–74), is a quartz diagram (two hundred axes) from the slate of the southern area, in which the flow cleavage appears as a relict structure. The specimen was collected along the Belvidere branch of the Pennsylvania Railroad, 1¼ miles south of the junction with the Delaware, Lackawanna, and Western Railroad at Manunka Chunk. All three *S* planes have been drawn into the diagram. S_2 was measured indirectly by determining its intersections with two joint surfaces; *b* was taken as the intersection of S_1 and S_2; and *b'* as the intersection of S_2 and S_3. The braided appearance of the rock in thin section (Fig. 5, *D*) results from the intersection of the two cleavages. The quartz grains average 0.035 mm. in diameter.

A study of the maximums indicates that *b'* has been of greater and more recent importance as an axis of rotation than has *b*. With *b'* as an axis of rotation, all maximums greater than 3 per cent fall either on the IV circle or in the zone between the IV and the VI circles. This type of orientation has been described by H. W. Fairbairn[23] in folded quartzites. If the diagram is rotated so that *b* is at the center, the following arrangement of maximums and submaximums may be seen—six between circles IV and VI and one within circle III. Further, these maximums are not arranged in girdles so completely as in the first case. It is possible that the 4 per cent submaximum nearest fabric axis *a* is the Maximum I already observed as characteristic of the flow cleavage (Fig. 8, *B*).

For these reasons, it appears that the original orientation about *b* has been destroyed and that a later one, developed by slipping and antithetic rotation along S_3, has been superposed. If this type of movement is the same as in the development of S_2, then the process has not gone so far. Further stretching of the fabric in *a'*, just as the rock was originally stretched in *a*, should result in the development of another Maximum I.

[23] "Hypotheses of Quartz Orientation in Tectonites," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1475–92.

SUMMARY AND CONCLUSIONS

The structures of the Paleozoic rocks indicate that they have been subjected to at least two periods of deformation. These structures might well be explained as the result of two peaks in the stress cycle of one period, were it not for the evidence of surrounding areas. Previous investigators (Behre, 1925; Miller, 1926; Stose, 1930) have shown that post-Ordovician, pre-Silurian folding took place. This has been correlated with the Taconic disturbance. The entire region was later affected by the Appalachian Revolution.

The flow cleavage of the Martinsburg formation may be dated as Taconic, since it parallels the axial planes of the folds of that disturbance. The bedding slip which accompanied the earlier stages of folding was superseded by slipping along cleavage surfaces. By this shearing movement, quartz orientation was developed which is believed to be typical Maximum I, in which both the optic axis and the major dimensional axis of quartz grains were aligned in the *a* direction. This pattern is associated with *ac* girdles resulting from folding, in which $b = B$. The external orientation forms the "grain" of the slate quarryman and is shown on the cleavage surfaces as a faint lineation.

The Appalachian orogeny is repre-

sented in this region by thrust faults and by a well-developed fracture cleavage. The Cambro-Ordovician and pre-Cambrian rocks exposed on Jenny Jump Mountain are, according to Bayley and Kümmel, underlain by a flat thrust fault. A reverse fault is present, but a flat overthrust is not supported directly by the field relations. At the only point where it could be observed, the fault plane dipped 40° southeast. Elsewhere all the evidence points indirectly to overthrusting. The flatly sheared silicified limestone beneath the gneiss of the Jenny Jump Mountain, the greatly stretched and broken formations of the footwall, and the isolated outlying limestone masses—all are characteristic of a thrust fault of considerable magnitude.

Although thrusting was the culmination of the process, the stresses that preceded it also had a strong effect upon the slate. These stresses, probably acting from the southeast (although with some small deviation from those of the Taconic orogeny), folded the flow cleavage and the bedding with it. Over much of the area, however, flow cleavage now parallels the bedding, which, especially in the massive sandy horizons, appears only slightly disturbed. Very similar relations exist between the two in the Mona complex in Anglesey. Edward Greenly[24] has explained it by isoclinal folding of flow cleavage between the thick uncleaved sandy layers. A secondary effect of the thrusting was the formation of fracture cleavage in the Martinsburg. This is seen up to a maximum distance of 3 miles north of the present fault trace. It bears the same relation to the flow cleavage as that structure bears to the bedding. The writer believes that this secondary cleavage was developed by the thrusting and overriding of the older rocks. Rotating and flattening of the cleavage layers by the same agent is evidenced by progressive flattening of their dip southward, as well as by the gradual change in character of the cleavage. Thus the cleavage was developed by shearing until it was well on the way to becoming a second flow cleavage. The progressive obliteration of the first flow cleavage was a necessary accompaniment. The degree to which the metamorphosis has advanced is clearly shown by the fabric analysis of the slate close to the overthrust, in which it appears that b' (the intersection of S_2 and S_3) = B. However, the flow-cleavage Maximum I has not developed. Evidently, considerable shearing under long-continued stresses is necessary for its formation. Fracture cleavage, commonly considered to be a minor structural feature, often remains unexplained or is lumped together with the other associated phenomena of flow cleavage. It is the contention of this paper that this is an area in which it can be definitely mapped as a regional structure and assigned to a specific cause—major thrust faulting. The opportunity of tracing the development of a cleavage as it is affected by stresses of progressively increasing intensity is of particular interest.

[24] "Foliation and Its Relation to Folding in the Mona Complex at Rhoscolyn (Anglesey)," *Quart. Jour. Geol. Soc.*, Vol. LXXXVI (1930), p. 171.

ACKNOWLEDGMENTS.—Ernst Cloos has been particularly helpful during the course of the work. The author also wishes to acknowledge the friendly criticism and advice of the late B. L. Miller and Walter H. Bucher. Mark H. Secrist, H. L. Alling, and Earl Ingerson kindly lent certain scientific instruments. The original of Figure 5, *A*, was lent by C. H. Behre, Jr. William Saunders, of the University of Rochester, assisted the author in the field during the 1939 season. C. L. McNulty, of Syracuse University, drew Figure 4.

PRELIMINARY NOTE ON VOLCANIC ERUPTIONS IN THE GOROPU MOUNTAINS, SOUTHEASTERN PAPUA, DURING THE PERIOD DECEMBER, 1943, TO AUGUST, 1944

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ABSTRACT

The phenomena and effects of new volcanic vents of the explosive type in the Goropu Mountains, Owen Stanley Ranges, Papua, are described on a basis of reports made by local observers. Petrological examination of lapilli from the vents indicates that an andesitic volcano has broken through ultrabasic rocks forming part of the Owen Stanley Ranges.

INTRODUCTION

Explosive volcanic activity has occurred since December, 1943, and is continuing spasmodically in the foothills of the Goropu Mountains, Papua, where previously no volcanic activity had been reported. Intervals between the first four recorded eruptions were 7, 23, and $5\frac{1}{2}$ weeks, respectively. The Goropu Mountains lie inland from Collingwood Bay (Fig. 1), 130 miles east of Port Moresby. The active vents, which are 40 miles south-southwest of Tufi government and mission station, broke through pre-Tertiary rocks, considered by E. R. Stanley[1] as Paleozoic or pre-Cambrian.

Although no volcanic activity had been reported previously from this particular locality, it is possible, since Stanley[2] has recorded hot springs and solfataric activity 65 miles to the west-northwest, that minor thermal activity may also have occurred in this unexplored area. It is unlikely, however, that violent explosive phenomena of the kind dealt with herein occurred within human memory, because of the relatively close proximity of mission and government stations to the active area, from which no previous reports of explosive vulcanicity have emanated.

REVIEW OF EYEWITNESS REPORTS

Prior to the explosive eruptions here described, columns of steam and ash from four volcanic vents were observed in October and November, 1943, and earth tremors had occurred during the previous two years, sometimes at the rate of two or three a day.

The first recorded eruption, that of December 27, 1943, ejected a crater-cloud of ash and steam to an estimated height of 15,000 feet. An electrical storm accompanied the eruption. No tremors or noises were reported from Tufi Station in connection with this eruption. Lapilli, carbonized wood fragments, and volcanic ash landed in native gardens at Iu-ai-u (U-ai-u), a coastal village 16 miles from the active vents. Fine ash and dust were thickly spread out on an 8-mile radius around the vents; mud rains and sulphurous vapors were recorded. Layers of white dust covered trees some distance from the vents. Bird life and leeches had vacated the area, but larger game was still abundant. Nearer the vents the dust layers were so thick that

[1] *The Geology of Papua* (Melbourne, 1923).

[2] "Geological Expedition across the Owen Stanley Range, 1916," *Ann. Rept., Papua, 1917–18* (1919).

the branches of trees were stripped off; all animal life had disappeared from the devastated region.

Ground patrols sent out by the district officer of the Australian Military Administration at Tufi noted that about 2 miles west of the vents there occurred in the devasted area two sheer-sided depressions, 50 feet deep and 100 feet across, which had stony floors but were water-

Wai-oa Creek, close to the area of the active vents. (Wai-oa Creek is a tributary of the drainage system, which enters the sea between Ganjiga and Ui-aku, as shown in Fig. 1). One of the chasms possessed a rim, 12 feet high and 60 feet long, occurring at intervals along either side of the chasm.

Mud rains, which fell during the approach of patrols to the active vents,

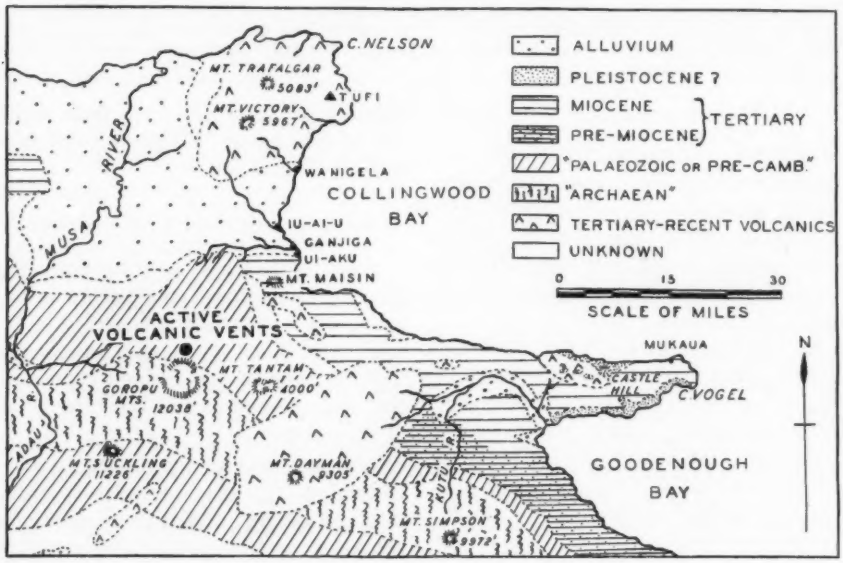

FIG. 1.—Geological map of the Collingwood Bay–Goodenough Bay area, showing site of the active volcanic vents. (Geology after E. R. Stanley, 1923; localities after W. M. Strong, 1916.)

less. In one of these chasms occurred a still further sunken area about 80 feet across and 6 feet deep. Its recent character was indicated by depths of dust greater than those occurring in the immediate neighborhood and by the uprooting of trees in the vicinity; no distinct crater could be discerned. Apparently, the disturbance had been of only sufficient strength to force dust up through the stony floor of the depressed area. Two larger, similar chasms were noted west of

covered the ground with 2 inches of mud. On the slopes of the Goropu Mountains, only the largest trees were left standing; they had been stripped of branches, and the trunks on the northern side of the vents were pitted right up to the top. All secondary plant growth had been broken down and covered with volcanic mud. This mud had an oily appearance, and its surface reflected trees that were still standing.

In the center of the region of activity,

one crater with sheer walls was estimated as 90 feet across and 60 feet deep. It was uncertain whether the bottom was covered with mud or solid material; sulphurous vapors were strong around this crater. Near by were two small craters in which the only sign of activity was a slight bubbling of the mud, and below these was an area of mud about three acres in extent, which emitted a white vapor. On a near-by ridge two large active craters gave off dense, brownish-colored steam and ash; stones were being thrown up in their vents. The heights of the cones around the craters were not estimated; but from the aerial photograph (Fig. 2) it can be seen that, even at later stages of eruption, they are relatively insignificant.

Crater-clouds persisted in the volcanic area for several weeks, and at approximately 8:00 P.M. on February 13, 1944, a further, but less severe, eruption than that of December, 1943, was observed from Wanigela, where an earth tremor was felt and explosions were heard coming from the vicinity of the active region. Figure 2, an aerial photograph taken on the following day from about 500–750 feet above the ground, shows a phase of this eruption. No stones or débris landed in the coastal villages of Iu-ai-u, Ui-aku or Ganjiga on this occasion, but some landed in the inland villages of Bonando and Kokoe, respectively 4 and 7 miles west from the coast and about 12 miles north-northeast of the active vents. The area of ash and dust deposits around the vents was considerably enlarged, extending up the slopes of the Goropu Moun-

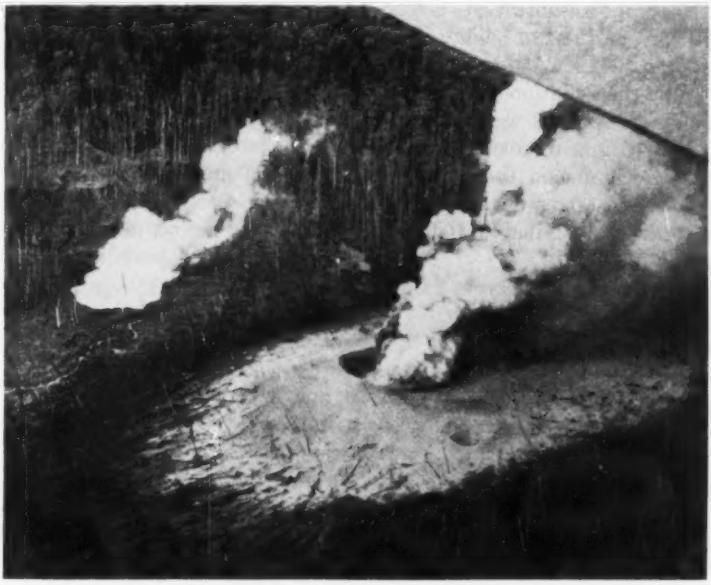

FIG. 2.—Active vents on the northern flanks of the Goropu Mountains, about 130 miles east of Port Moresby, Papua. Eruption of February 14, 1944. Note craterlet on flanks of cone in foreground, and symmetrical outline of main crater. (Department of Information photograph.)

tains and increasing the area of devastation in the tropical jungle to at least 20 square miles. No further vents beyond the original four were observed.

These earlier eruptions of the Goropu volcanic vents were evidently directional, as indicated by the pitting of the trunks of trees on the northern side of the vents and by the fact that lapilli were discharged to the north-northeast, landing at the villages of Iu-ai-u, Ui-aku, Ganjiga, Bonando, and Kokoe.

Dust from the eruption of February 13, 1944, was swept in a westerly direction by high-altitude air currents, resulting in the enveloping of the Coral Sea and Port Moresby (130 miles away to the west) in a thick pall of dust on February 14, 1944.

War-correspondent observers from a plane, which flew over the vents on February 14, reported volcanic dust hanging out in thin layers from stratus clouds and stretching for miles out to sea and up into the mountains, where it concentrated along the valleys. The heat from one of the vents could be felt at heights of 500 feet above it; at lower levels the heat was unbearable, the vapors from the crater were nauseating and had a strong sulphurous odor. What appeared like lava streams were reported passing through the brown mud around the vent, but no lava flows have yet been confirmed by ground patrols. The observed phenomena may have been hot or cold avalanches.[3] The crater appeared from the air like "an oversize bomb crater," largely masked by steam; in its center was a dull red glow, but no apparent lava stream issued from the vent itself. A great, dazzling-white pillar of steam rose some 2,000 feet above the crater.

Later observations, made early in March, 1944, along the course of the Ui-aku Creek, south of Mount Maisin (Fig. 1), indicated that the Ui-aku Creek carried unusually large volumes of water, highly charged with mud, while considerable amounts of silt with large blocks of vesicular rock had been deposited along its banks. All of the mud was being brought down by a branch of Ui-aku Creek from the area of the volcanic vents.

Numerous small, newly developed streams, which flowed at random over the surface, were also charged with silt and vesicular rock. They obviously had their origin principally in the mud rains formed by the condensation of the discharged vapors on dust particles, and probably represent the initiation of a new local drainage system in place of stretches of Wai-oa Creek, reported to have dried up in parts since the inception of volcanic activity. Dislocation of the former drainage system is also indicated nearer the center of the devastated area; the valley of a large creek that originally flowed through flat, gradually sloping country covered with dense jungle growth is now represented by a ridge, narrow below, and widening to half-a-mile or so across near the craters. This ridge is cut by a creek flowing partly into Ui-aku Creek and partly into its former bed near Mount Maisin. The ridge consists of "nothing but baked earth, reddish in color and with a very loose crumb structure." It probably represents a volcanic mudflow of the type known as a *lahar* in Java,[4] where the so-called mud is a mixture of water and ash containing blocks and fragments of rock of various sizes.

White vapors (principally steam),

[3] F. A. Perret, "The Vesuvius Eruption of 1906," *Carnegie Inst. Wash. Pub. No. 339* (1924), p. 49.

[4] L. M. R. Rutten, "Voordrachten over der Geologie van Nederlandsch Oost-Indië," *Den Haag* (1927), pp. 149–54.

which rose through cracks 6 inches to several feet long in the ground around the active vents, were sufficiently hot to boil water, while stones on the surface were too hot to handle.

The vents were still pouring forth fumes at the end of April, 1944, three of them continuously and one spasmodically.

At 8:45 A.M. on July 23, 1944, there was a further explosive eruption of the Goropu craters, dust again being strewn over an extensive area, increasing the region of devastation to 30 square miles. All minor vents had been sealed up, and the main crater, now 500 yards across, had commenced to build up its cone with greater rapidity. Blocks of vesicular rock weighing up to 2 pounds were found at Wo-Wo Gap, 15 to 20 miles distant.

On August 31, 1944, dust from a later eruption fell on Port Moresby.

PETROLOGY OF THE EJECTED MATERIALS

Approximately two dozen samples of lapilli and three ejected pebbles were submitted for investigation at the Melbourne University geology department. The lapilli were collected from near Iuai-u village, 16 miles from the center of the eruption. Eight samples were employed in the petrological investigations and six in the chemical analysis (Table 1).

Macroscopic investigation shows that the lapilli vary in size from $1 \times \frac{1}{2} \times \frac{5}{8}$ inch to $1\frac{3}{4} \times 1\frac{1}{2} \times \frac{5}{8}$ inches. The lapilli are of irregular shape (Fig. 3, *A–I*), their color is light gray, their texture vesicular, although the number of vesicles varies in different specimens. Polished surfaces show darker colored minerals, mainly up to 1 mm. long, set in the light-gray matrix. A few dark crystals up to 6 mm. in length were isolated from parts of the matrix.

Microscopic examination emphasizes the vesicular character and porphyritic texture of the rock, while also revealing a fluidal arrangement of many of the constituent minerals in some, but not all, of the lapilli.

The rock conforms with A. Johannsen's[5] description of a biopyribole ande-

TABLE 1

	1	2	3
SiO_2	55.83	54.56	54.14
Al_2O_3	16.23	16.49	16.42
Fe_2O_3	nil.	1.02	1.69
FeO	4.13	5.65	5.26
MgO	7.91	8.57	8.44
CaO	7.87	7.95	8.05
Na_2O	2.30	2.07	2.20
K_2O	3.80	3.35	3.34
H_2O+	0.67	0.15	0.56
H_2O-	0.34	.....	.....
CO_2	n.d.	.....	.....
TiO_2	1.14	1.10	1.23
P_2O_5	n.d.	.....	.....
MnO	0.11	tr.	tr.
Total	100.33	100.91	101.33

NORMS

	1	2	3
Q	3.00	.....	.....
Or	22.24	20.02	20.02
Ab	19.39	17.29	18.34
An	22.80	25.85	25.02
di	12.95	10.87	11.98
hy	19.39	21.27	18.19
ol	.....	1.25	2.43
mg	.....	1.39	2.55
il	.....	2.00	2.28

NOTES

1. Lapilli (andesite), Goropu Mountains, Papua (anal. F. F. Field).

2. Gray andesite, Radicofani, Tuscany (anal. H. S. Washington, *Amer. Jour. Sci.*, Vol. IX [1900], p. 52).

3. Black andesite, Radicofani, Tuscany (anal. H. S. Washington, *Amer. Jour. Sci.*, Vol. IX [1900], p. 52).

The rock conforms with A. Johannsen's[5] description of a biopyribole ande-

[5] *A Descriptive Petrography of the Igneous Rocks* (Chicago: University of Chicago Press, 1937), Vol. III.

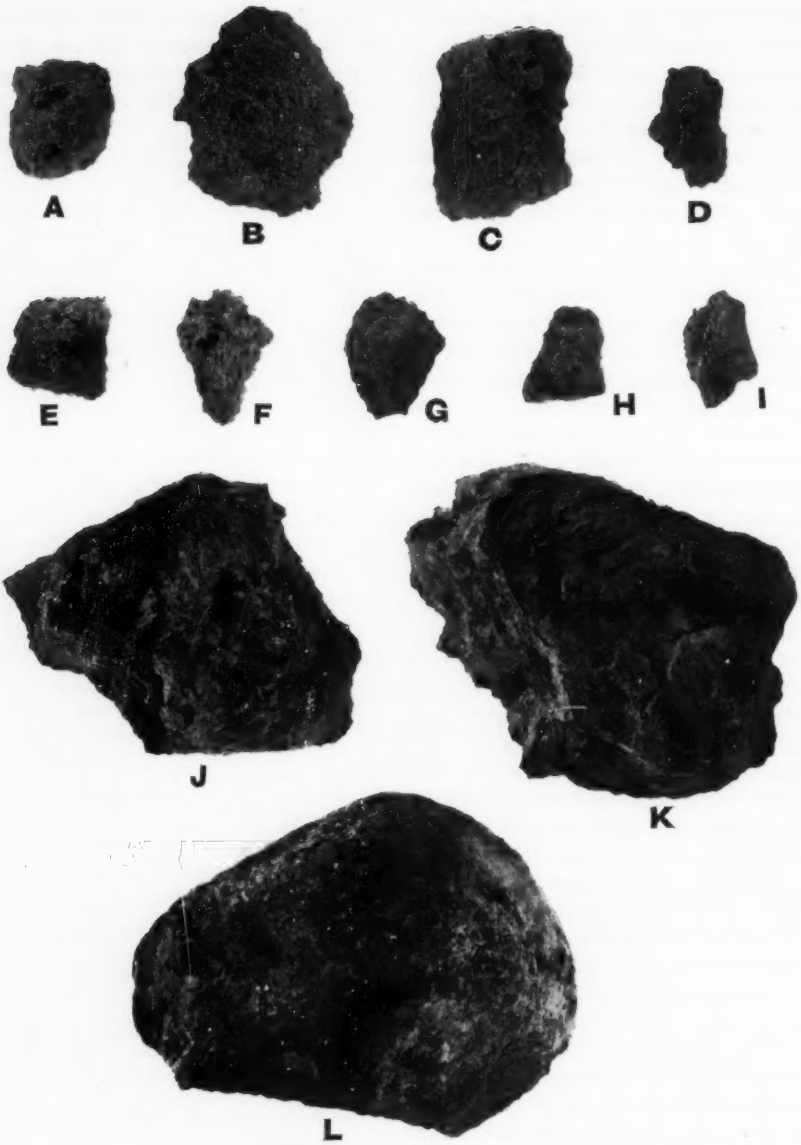

FIG. 3.—Ejectamenta from the Goropu volcano, Papua.

A–I: Lapilli (andesitic) collected from Iu-ai-u; thrown 16 miles by the eruption of December 27, 1943. ×0.7.

J–L: Ejected pebbles from near the vents; eruption of December 27, 1943. Approximately natural size.

site in containing four different ferromagnesian types of minerals, namely, crystals of augite, biotite, hornblende (in two examples), and olivine (Fig. 4), set in a microcrystalline to hyaline base. The chief mineral appears as numerous, small, colorless prisms of augite in subparallel alignment. A few phenocrysts of pale-green augite show partial inversion to hornblende or to biotite; one phenocryst, altered to biotite on the outside, measured $6 \times 2 \times 1\frac{1}{2}$ mm. Biotite (R.I. = 1.613), as brown, elongated plates showing good alignment in the fluidal structures, constitutes the next most abundant crystallized component of the rock. Occasional basal plates of this mineral reveal small inclusions, some of which are remnants of augite, after which the biotite crystallized; others are crystals of apatite. Hornblende is next in abundance in two of the lapilli, forming some of the larger phenocrysts (up to 3 mm. long) in the rock; it is of greenish-brown color, sometimes zoned, sometimes twinned. Olivine is represented by infrequent clots, which show partial resorption and transition to biotite.

The microcrystalline to hyaline base contains abundant minute grains of ilmenite and small laths of andesine. Numerous needles of apatite and minute rounded grains of colorless garnet form accessory minerals in the groundmass. The glassy matrix is grayish to colorless and varies in amount in different lapilli. The garnet is common in one of the lapilli, but scarce in others.

With bromoform of specific gravity 2.88, a heavy-mineral index figure of 15.5 was obtained. Most of the minute garnets were carried up in the bromoform by virtue of being included in the glass of the groundmass; a few, however, were observed as inclusions in augite.

The chemical composition and the norms of the lapilli are indicated in Table 1, column 1, and are compared with two analyses of andesites from Radicofani in Tuscany, Italy. Unusual features of the rock, as disclosed by the chemical analysis, are the low total iron content, the apparent absence of Fe_2O_3, the excess of K_2O over Na_2O, and the high content of MgO, which is slightly in excess of CaO.

Most andesites have lime in excess of magnesia and soda in excess of potash, while iron is generally more abundant. The low iron content of the Goropu lapilli indicates that the olivine and the augite are magnesia-rich varieties. The high content of MgO is a reflection of the presence of olivine crystals and also, taken in conjunction with the absence of Fe_2O_3, suggests that the biotite is a magnesia-rich variety. The high content of MgO in the presence of a relatively high SiO_2 content is anomalous. This may be due to the inclusion in a moderately acid magma of xenocrysts of magnesia-rich minerals, derived from the ultrabasic basement rock through which the volcano has broken in the Goropu Mountains. Alternatively, the lapilli may represent differentiation products within a cupola,[6] from which some of the magnesia-rich xenocrysts may have sunk prior to crystallization. The fact that potash is present in excess of soda and that soda would be used up in the formation of andesine indicates that the residual glass in the lapilli is potash-rich. Some of the potash may have entered into the composition of the biotite, but it appears that, if the rock had become holocrystalline, it would have had as much orthoclase as plagioclase and would then enter into the category of the trachy-

[6] "Tertiary Lavas from the Kerguelen Archipelago," *Repts. British–Australian–New Zealand Antarctic Research Expedition, 1929–1931*, Ser. A., Vol. II, Part 5 (1938), pp. 72–100.

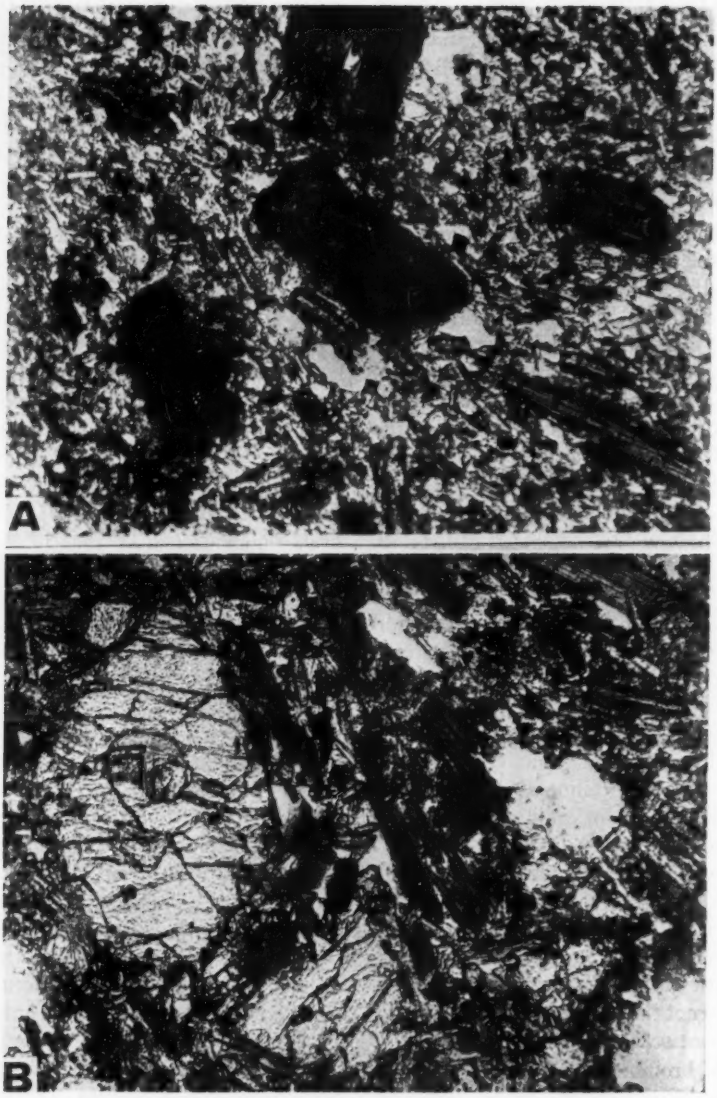

FIG. 4.—Photomicrographs of lapilli (andesitic) from the Goropu volcano, Papua.

A: Hornblende and biotite phenocrysts, and short prisms of augite in a glassy, vesicular groundmass. ×85.

B: Olivine clot and associated biotite in a glassy groundmass containing augite prisms, small feldspar laths, and occasional vesicles. ×100.

andesite group of rocks. The mineralogical and chemical evidence thus indicates that the lapilli from the craters in the Goropu Mountains of Papua represent augite-biotite-hornblende-olivine trachyandesite.

The analyses of two andesites from Radicofani in Tuscany, Italy, provide the nearest analogues to the andesitic lapilli from the Goropu volcano; all three come into the same category—II. 5. 3. 3.—in the Cross, Iddings, Pirsson, Washington classification of rocks.

The three ejected pebbles (Fig. 3, *J–L*) were $2\frac{3}{4} \times 2 \times 1\frac{3}{4}$ inches, $2\frac{1}{2} \times 1\frac{3}{4} \times 1\frac{3}{4}$ inches, and $2 \times 1\frac{1}{2} \times \frac{3}{4}$ inches in size. They were collected from the site of one of the active vents and are "dry pebbles," having been rounded to varying degrees by having been repeatedly thrown up in the throat of the volcano, prior to expulsion from the crater. Each specimen was coated with a thin covering of fine volcanic mud.

Two of the ejected pebbles are of ultrabasic igneous character, and the third intermediate; they represent portions of the wall rock of the vent, up which the volcanic ejectamenta rose. The two ultrabasic ejected pebbles are dark green in color and consist of propylitized serpentine rock with augite. They were probably originally pyroxenite and now contain secondary chlorite, quartz, feldspar (adularia?), limonite, and numerous patches of brownish-gray carbonate, probably magnesite. Some epidote is present in both ejected pebbles, and a vein of zoisite cuts through the serpentine in the more propylitized of the two. These pebbles of ultrabasic rock evidently originated from "the long but broken serpentine belt" associated with the Owen Stanley series and "occurring on the northern slopes of the Main Range from the headwaters of the Waria river to the Peninsula between Milne Bay and the south coast."[7]

The third pebble is a lighter-green, dense, fine-textured rock with a microporphyritic character. Microphenocrysts of augite are set in a microcrystalline to cryptocrystalline and hyaline groundmass. Andesine is recognizable among the groundmass minerals, and its minute, lathlike crystals are arranged sometimes in a subparallel fluidal fashion, sometimes in a felted mass, so that the ground mass is thus partially trachytic to pilotaxitic in structure. From the evidence of thin-section examination, the rock is best described as an augite andesite. It was carried up from depth as a solid rock and ejected as such.

These three ejected pebbles supply some evidence of the nature of the basement rock through which the new volcanic vents have broken on the northern flanks of the Goropu Mountains in Papua.

A sample of the dust which fell on Port Moresby on August 31, 1944, was composed principally of rock and mineral fragments which averaged 0.2 mm. in size. The particles consist of andesitic glass with embedded prisms of augite, individual plates of fresh and chloritized biotite, occasional fragments of hornblende, augite, and olivine. Rare fragments of quartz, calcite, oligoclase feldspar, and one crystal of rutile, observed in two mounted preparations of the dust, were probably picked up from the atmosphere during the movement of the dust cloud from the Goropu volcano to Port Moresby. Shreds of vegetable matter were also present in the dust.

REMARKS

The geological position of the volcanic vents is a matter of considerable interest,

[7] Stanley, p. 29 of ftn. 1 (1923).

as no volcanic phenomena had previously been reported in the scientific literature from this particular locality. No detailed geological map of the Goropu volcanic area exists, and the basis for boundaries drawn through this zone on the general geological map of Papua (of which Fig. 1 of this paper is a portion) has not been stated. E. R. Stanley[8] reported that recent outflows of lavas and pyroclastics had occurred about the headwaters of the Musa and Kumusi rivers, 65 miles west-northwest of the recently active volcanic zone, stating:

> Trachyte lavas were met with near Vi Creek on the Mimai river, and about 2 miles up the Awaru river from its junction with the Moni. At this latter locality, I discovered a series of hot springs on the left bank of the river about two chains from the levée. The atmosphere for a considerable distance round was contaminated with sulphuretted hydrogen. The ground near the vents is very hot, cracked and devoid of vegetation. The vents are from 18 inches to two feet in diameter, incrusted with siliceous sinter, geyserite, sulphur, and small red incrustations consisting of selenium and cinnabar. The vents are in schistose country, about which there are large masses of volcanic agglomerate. The natives evidently did not know of this occurrence and were very frightened when approaching it, especially when the small eruptions occurred every four and a half minutes.

Stanley (1923) also stated that thermal areas are seen to advantage on the islands of Normanby and Fergusson and about Mount Victory, which was then regarded as the only active volcano in the Territory of Papua.

A zone of volcanic and fumarolic activity (sulphur and steam emanations), possibly connected with rifts, extends from the D'Entrecasteaux Islands, through the Cape Vogel and Cape Nelson peninsulas (see Fig. 1) to the headwaters of the Kumusi River. R. W. Van Bemmelen,[9] in his recent analysis of the geotectonic structure of New Guinea according to his "Undation Theory," refers to this volcanic zone on the north coast of southeastern New Guinea as follows:

> This zone of young volcanic activity extends eastwards in the D'Entrecasteaux Group with Mt. Dawila on Goodenough Island. One gets the impression that here, since the Lower Miocene orogenesis .... a small secondary undation cycle spreads from the Central Range towards the north. This so-called "D'Entrecasteaux-system" has a volcanic inner arc (D'Entrecasteaux Islands with the volcanic zone along the northern side of the tail of New Guinea) and a non-volcanic outer arc (Trobriand Islands and Woodlark Island).

Figure 5 shows the position of these arcs in relation to the volcanic zones of the Territory of New Guinea, which have been studied recently by N. H. Fisher[10] and L. C. Noakes,[11] and to other structural elements recognized in the New Guinea area.

The numerals and letters in the Structural Sketch Map of New Guinea (Fig. 2) signify:

1. Neogenic–Quaternary volcanic zones or volcanic inner arcs
2. Folded and overthrust nonvolcanic arc of the Banda System
2a. Median depression of the Banda outer arc
3. Nonvolcanic outer arcs of the Bismarck and the D'Entrecasteaux systems
4. Central Range of New Guinea
5. Northern Divide Range
6. Merauke ridge (*sensu lato*)

[8] Ftn. 2 (1919).

[9] "The Geotectonic Structure of New Guinea," *De Ingenieur in Nederlandsch-Indie*, Yaarg. 6, No. 2, Vol. IV (1939), pp. 17–28.

[10] "Geology and Vulcanology of Blanche Bay and the Surrounding Area, New Britain," *Geol. Bull. No. 1, Territory of New Guinea* (1939); "Report on the Volcanoes of the Territory of New Guinea," *Geol. Bull. No. 2, Territory of New Guinea* (1939); "The Volcanoes of the Mandated Territory of New Guinea," *Proc. 6th Pacific Sci. Cong.*, Vol. II (1940), pp. 889–94.

[11] "Geological Reports on New Britain," *Geol. Bull. No. 3, Territory of New Guinea* (1942).

7. Australian continental block
8. Melanesian semicontinental region
8*a*. Crystalline schists of Melanesian border

(The northern and southern depression zones of the Island of New Guinea are left blank. The volcanic and nonvolcanic arcs of the D'Entrecasteaux System are marked, respectively, *V* and *N*).

The andesitic character of the Goropu volcano, as evidenced by the lapilli, fits chemical analyses of several Japanese and other andesitic volcanoes in the circum-Pacific belt with that of the Goropu volcano shows that the New Guinea example has distinctive characters (see Table 1); these have already been elaborated; no analyses of other New Guinea or of any New Britain andesites of geologically Recent age are available for comparison.

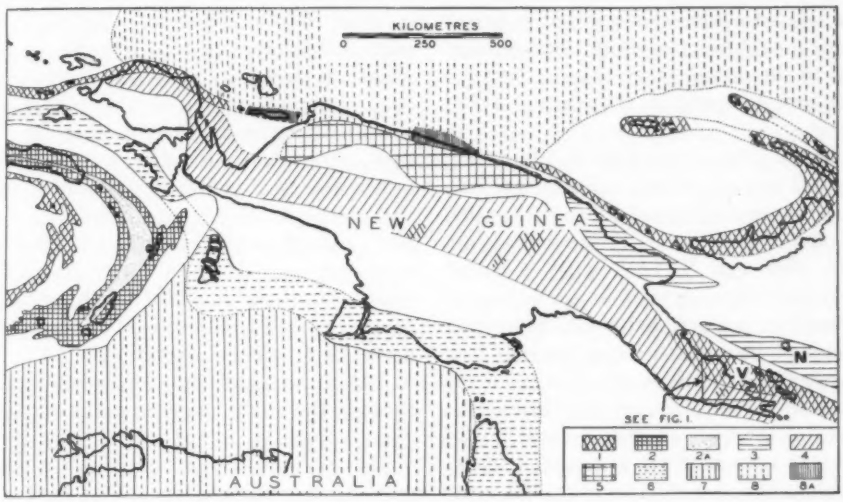

FIG. 5.—Structural sketch map of New Guinea. (After R. W. Van Bemmelen, 1939)

in well with the fact that the geologically Recent and present-day volcanoes girdling the Pacific Ocean erupt andesites. Many of these are hypersthene-bearing varieties,[12] but this mineral does not occur in the new Goropu volcanic ejectamenta which have been investigated. Fisher[13] described most of the recent New Guinea and New Britain volcanoes as basaltic in character, but in parts andesites have been recorded from thin-section examinations. Comparison of the

Computation of the standard mineral composition of average andesites shows a certain excess of free silica. This is expressed in the Goropu volcanic lapilli by the presence of 3 per cent normative quartz, and the free silica here must lie occult in the glassy to microcrystalline groundmass. In addition to excess silica, however, there occur sporadic olivine crystals; rocks with such associations are regarded by A. Lacroix[14] as doliomorphic.

Apparently the lapilli and, most likely,

[12] G. W. Tyrrell, *The Principles of Petrology* (London: Methuen & Co., Ltd., 1934).

[13] Ftn. 10 (1939).

[14] "La notion de type doliomorphe en lithologie," *Comp. rend. Acad. sci., Paris*, Vol. CLXXVII (1923), pp. 661–65.

the large blocks of vesicular rock reported by patrols as occurring along Uiaku Creek represent parts of an almost solidified plug or cupola which blocked the initial rift developed above the magma chamber, or they represent an even deeper-seated plastic magma and may have formed part of a chilled margin at the roof of the magma chamber. The plug or chilled margin ultimately became disrupted by gas pressure when the accumulated gases below exerted sufficient force for explosive activity to take place. Up to the present time this activity has not been followed by the pouring-out of lavas.

Some measure of differentiation and crystal resorption had occurred prior to eruption, as evidenced by the alteration of olivine and augite phenocrysts to biotite. Although N. L. Bowen[15] regarded volatile components as of minor importance in the fractional crystallization of magmas, he nevertheless accepted C. N. Fenner's[16] hypothesis of a process of gas transfer as causing igneous differentiation, as far as it affected magma bodies open to the air, where a streaming of gas bubbles through the magma could bring about a differential transfer of materials. Bowen[17] considered that, at best, surface lavas and volcanic conduits were unimportant seats of igneous differentiation. It seems, however, that such effects may be locally important, and, although transient, the process of gas streaming through the magma below the Goropu volcanic vents has apparently had marked effects. Besides resulting in vesiculation, the passage of escaping gases and aqueous substances through a magma from which olivine and augite crystals had already separated has apparently played a decisive role in the formation of hornblende. Owing to a transient enrichment in volatile components, equilibrium changes caused suitable conditions from which wet-fusion minerals could form, and so hornblende crystallized. Equilibrium under these conditions, however, was not maintained, because small augite prisms were developed in the groundmass when volatiles had escaped from the magma, that is, the magma had returned to a state from which dry-fusion minerals again crystallized. The extrusion of the partially solidified magma in the form of lapilli at this stage interrupted the normal plutonic processes involving the resorption and sinking of olivine and augite crystals and resulted in the retention of an assemblage of abnormal mineralogical types; the olivine persisted only by virtue of the rapidity of cooling consequent upon the rapidity of extrusion.

Rapid ascent of the plastic material through the vents, under the stimulus of great expansive forces created by the further accumulation of gases below the more plastic magma, resulted in marked decreases in the temperature and pressure of the partially solidified rock. Consequent quick chilling of the interstitial liquid led to the formation of a glassy matrix charged with numerous small vesicles. This may have occurred partly during ascent through the conduit, but probably mainly during flight through the atmosphere, when discharged as ejectamenta. During these final stages of consolidation, a flow structure was developed in the lapilli, to a greater degree in some than in others.

It would appear that the magma reservoir or, at the least, the upper parts of it are probably in a well-advanced stage of solidification in the Goropu region of volcanic activity. No recent flows

[15] *The Evolution of the Igneous Rocks* (Princeton: Princeton University Press, 1928).

[16] "The Katmai Magmatic Province," *Jour. Geol.* Vol. XXXIV (1926), pp. 675–772.

[17] P. 294 of ftn. 15 (1928).

of lava are known from the immediate vicinity of this center of vulcanism, and, moreover, the lapilli indicate that considerable crystallization had gone on in depth prior to the explosive eruptions. As far as the Papuan region as a whole is concerned, vulcanism in general is apparently approaching the dying stages, because the last flows of andesitic lavas known to have been extruded are recorded as having occurred in Pliocene to Pleistocene times at Mount Dayman and in the Cape Nelson region.[18] Known activity in historical times has been mainly explosive or else has produced only sinter and gaseous and sulphurous emanations—phenomena usually interpreted as indicating the dying stages of volcanic activity.

From the available eyewitness accounts and according to B. G. Escher's[19] classification of central eruptions, it seems that the Goropu volcano probably belongs to a less violent class of the *Perret* type of eruptions, that is, one of the destructive variety connected with very strong gas pressure, a very deep magma chamber, and a viscous lava. A high gas pressure is indicated in an eruption by a high cauliflower cloud of ash and steam, and, according to Escher,[20] high gas pressure is observable only when the amount of escaping gas is very great, as evidenced by the long duration of a violent eruption or by the coring and scouring effect on the vent. The columns of crater-clouds from the Goropu volcano were of considerable magnitude after the explosive eruptions. The continued emission of gas, steam, and ash through the vents between December, 1943, and July, 1944, with three strong eruptions during that period, and the tearing-away, carrying-up, and ejection of portions of the walls of the vents indicate the development of high gas pressure in the Goropu region of vulcanicity. Such a condition is probably to be compared with the intermediate gas phase, as described by Perret[21] for the 1906 Vesuvius eruption.

The Goropu vents have not, as far as is known, emitted any lavas, and it therefore appears that the effusive liquid phase is absent. On the other hand, the vents cannot be classified as entirely explosive in type, because for a goodly proportion of their period of activity to date there have been steadily issuing currents of gas from most of the vents. Such gaseous emissions are not to be looked upon as coming completely into the category of "explosions." Only occasionally have explosions occurred; this may explain why the cones have so far remained as relatively insignificant features of the Goropu volcano; gas, steam, and fine ash are the principal constituents emitted, and the fine ash is carried away for some considerable distance from the centers of eruption.

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[18] Stanley, ftn. 1 (1923).

[19] "On a Classification of Central Eruptions According to Gas Pressure of the Magma and Viscosity of the Lava," *Leidsche geologische Mededeel.*, Vol. VI (1933), pp. 45–49.

[20] *Ibid.*, p. 46.

[21] Pp. 44–47 of ftn. 3 (1924).

GEOMORPHIC TERMINOLOGY AND CLASSIFICATION OF LAND MASSES

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ABSTRACT

The words "plains," "plateaus," and "mountains" have been used by W. M. Davis, Douglas Johnson, and A. K. Lobeck to mean crustal masses made up of flat-lying strata or deformed and intruded rocks. The writer criticizes this usage and proposes that it be abandoned in favor of the commonly understood topographic meanings of the words. An alternative set of terms, already often used, is suggested for the various land-mass types. It employs only common geologic words, which describe the underlying structures. A geomorphic classification of areas of intrusive, metamorphic, and complexly deformed rocks is proposed.

INTRODUCTION

In the teaching of geomorphic principles, map interpretation, and regional geomorphology it is necessary to classify land masses on the basis of their geologic structure, in keeping with W. M. Davis'[1] principle that all land forms are the product of three basic elements: *structure*, *process*, and *stage*. Land forms underlain by a given type of geologic structure may be divided into two major groups. The first consists of land forms produced directly by epeirogenic, orogenic, or volcanic activity. These have been termed "initial" or "constructional" land forms and are dominant in initial and youthful stages of the erosion cycle. The second group consists of land forms developed by gradational agents, which carve the relatively large initial land forms into a variety of smaller "sequential" or "destructional" forms.

While these broad concepts of landform development have proved invaluable, the writer has encountered difficulty in explaining to students of elementary geomorphology certain of the terms applied by Davis,[2] Douglas Johnson,[3] and A. K. Lobeck[4] to specific classes of geologic structures, grouped under the headings "Plains and Plateaus" and "Mountains." In tabular form is given the system employed for many years by Johnson and Lobeck, and fully published by the latter.[5]

1. Plains and plateaus (simple structure)
   a) Interior plains
   b) Plateaus
   c) Coastal plains
2. Mountains (disturbed structures)
   a) Folded mountains
   b) Dome mountains
   c) Block mountains
   d) Complex mountains
3. Volcanoes and related forms

Criticism of this terminology rests upon the following points: (1) The words

[1] "The Geographical Cycle," *Geog. Jour.*, Vol. XIV (1899), pp. 481–504.

[2] *Geographical Essays*, ed. Douglas Johnson (Boston: Ginn & Co., 1909).

[3] References to Johnson's terminology and classification of land forms are based upon his class lecture notes.

[4] *Panoroma of Physiographic Types* (New York: Geographical Press, Columbia University, 1926); *Geomorphology* (New York: McGraw-Hill Book Co., 1939).

[5] See ftn. 4 (1939).

"plain" and "plateau" have been taken from their usual meaning in terms of topography and have been redefined as crustal masses whose geologic structure consists of horizontal strata; (2) the word "mountains" likewise has been deprived of its usual meaning as a topographic feature and has been redefined as any large crustal mass of deformed rock; (3) the class "complex mountains" includes a wide variety of rocks and structures, certain of which have simple, rather than complex, topographic expression.

Discussions with graduate students and experimental modification of this terminology in teaching have indicated that the difficulties can easily be alleviated without changing Davis' principles of land-form development. Moreover, an advantage in using geological and geographical terms in their generally accepted sense, instead of as redefined and highly specialized terms, is to be gained through the easier understanding of geomorphic literature by those in other fields who cannot take time to refresh their memories regarding special meanings. Seemingly unsatisfactory elements of the terminology are here examined, and alternatives are proposed.

The writer is indebted to several persons who have kindly read and criticized the manuscript. These include Professors A. K. Lobeck and W. H. Bucher, of Columbia University; Professor Kirk Bryan, of Harvard University; Professor Karl Ver Steeg, of the College of Wooster; Professor Henry S. Sharp, of Barnard College; and Mr. Charles W. Carlston, of the United States Geological Survey. It should not be inferred, however, that these persons necessarily indorse the opinions stated here.

PLAINS AND PLATEAUS

REVIEW OF USAGE

The practice of calling regions of horizontal strata "plains" and "plateaus" seems to have been introduced by Davis in 1884.[6] But in 1893[7] he referred to the New England Upland as a plateau and to the "plateau of the middle Rhine." Here he clearly used the conventional geographical meaning of the word "plateau." By his reference to regions of complex geologic structure, he ruled out any implication of horizontal structure. In 1894 Davis[8] referred to "plains and plateaus of horizontal structure" as if feeling the need of accompanying the words with a translation into terms of geologic structure. In 1896 Davis'[9] use of the title "Plains of Marine and Subaerial Denudation," as well as the repeated use of "plain" throughout the paper as a surface of low relief, shows that on occasion he did abandon entirely the meaning of the word as "horizontal structure." Soon after the turn of the century, the use of "plains" and "plateaus" for land masses of horizontal structure had become well established in Davis' writings.[10]

Douglas Johnson subscribed to Davis' terminology and classification of the constructional land forms. In map-inter-

[6] "Geographic Classification, Illustrated by a Study of Plains, Plateaus, and Their Derivatives" (abstract), *Proc. Amer. Acad. Arts and Sci.*, Vol. XXXIII (1884), pp. 428–32.

[7] W. M. Davis, "The Improvement of Geographical Teaching," *Nat. Geog. Mag.*, Vol. V (1893), pp. 68–75.

[8] "Physical Geography as a University Study," *Jour. Geol.*, Vol. II (1894), p. 96

[9] "Plains of Marine and Subaerial Denudation," *Bull. Geol. Soc. Amer.*, Vol. VII (1896), pp. 377–98.

[10] *Physical Geography* (Boston: Ginn & Co., 1898); *Die erklärende Beschreibung der Landformen* (Leipzig, 1912).

pretation classes he used the combination term "plains-plateaus" to designate any region underlain by horizontal strata. Lobeck has followed Davis and Johnson in the *Panorama of Physiographic Types*[11] and the textbook *Geomorphology*.[12]

Fenneman has followed Davis in the use of "plain" and "plateau" and has exerted a dominant influence in naming and describing the geomorphic provinces of the United States.[13]

A. D. Howard and L. E. Spock[14] have recently used "plain" and "plateau" in the sense of horizontal strata, although they present a new system of land-form classification.

A survey of the literature reveals that many geomorphologists and the larger proportion of geologists in other fields and geographers have preferred to use the words "plain" and "plateau" much as they are defined by *Webster's New International Dictionary*.[15] This source defines "plain" as "level land" or a "broad stretch of land having few inequalities of surface." "Plateau" is defined as "a tract of land of considerable summit area, which is high, or distinctly above adjacent land on at least one side; a tableland." In neither definition is mention made of underlying rock structure. A few random examples of this usage are given below.

In his essay on the development of physiographic features, J. W. Powell[16] used "plains" and "plateaus" for relatively flat land surfaces. James Geikie,[17] treating the origin and development of land forms, used "plains" and "plateaus" in the same way. C. A. Cotton[18] has consistently used these words in their topographic sense. For example, he states that past periods of peneplanation in mountains "may be recognizable as such owing to the preservation of plateaux or plateau remnants." When referring to regions of low relief underlain by horizontal strata, he keeps the distinction between surface form and structure clear by such terms as "stripped structural plateau" or "structural plateau."[19]

E. de Martonne[20] employs a system of land-form classification based upon structure and including classes similar to those used by Davis, Johnson, and Lobeck; but he uses the word "plain" to describe land surfaces of low relief and does not apply it to strongly elevated or maturely dissected horizontal strata. The restriction of "plain" and "plateau" to land surfaces, irrespective of rock structure, is evident in his statement that there are regions of plains and plateaus where geologic studies have revealed bedrock of highly complex tectonic structures.

C. R. Longwell, A. Knopf, and R. F. Flint[21] do not follow Davis' terminology. They state:

[11] See ftn. 4 (1926).

[12] See ftn. 4 (1939).

[13] "Physiographic Divisions of the United States," *Annals Assoc. Amer. Geog.*, Vol. XVIII (1928), pp. 261–353; *Physiography of the Western United States* (New York: McGraw-Hill Book Co., 1931). *Physiography of the Eastern United States* (New York: McGraw-Hill Book Co., 1938).

[14] "Classification of Landforms," *Jour. Geomorph.*, Vol. III (1940), pp. 332–45.

[15] 2d ed., Springfield, Mass.: G. & C. Merriam Co., 1942.

[16] "Physiographic Features," *Nat. Geog. Soc., Mono. I* (1895), pp. 34–40.

[17] *Earth Sculpture* (New York: G. P. Putnam's Sons, 1898), pp. 335–39.

[18] *Landscape* (Cambridge: Cambridge University Press, 1941), p. 83.

[19] *Ibid.*, pp. 101–2.

[20] *Traité de géographie physique*, Vol. II (Paris: Librairie Armand Colin, 1926), pp. 563–68, 756–76, 807.

[21] *Outlines of Physical Geology* (New York: John Wiley & Sons, 1941), p. 296.

High plateaus formed by any process are attacked by stream erosion, and during a late stage in the destruction some residuals in the more favored locations have sufficient height, in relation to their surroundings, to be called mountains.

As an example they cite the Catskill Mountains. They also add:

In some plateaus the rocks are steeply tilted strata whose edges were cut down to a nearly uniform level at a low elevation by previous erosion.

Here, clearly, the term "plateau" is applied to a topographic feature, quite apart from any particular rock structure underneath.

In recent works on geography examined by the writer, the words "plain" and "plateau" are used in the topographic sense. For example, Preston James[22] defines "plain" as an area of low relief, generally less than 500 feet. He states that a plateau stands distinctly above neighboring areas, at least on one side, and has a considerable part of its surface at or near summit level. V. C. Finch and G. T. Trewartha[23] discuss at length the development of landscape features through the activity of erosional processes upon geologic structures, but they classify land forms primarily on the basis of relief and only secondarily on the basis of rock structure or geologic process. "Plain" and "plateau" refer to surface form of the land, regardless of the nature of the underlying rocks and structures. George B. Cressey[24] restricts "plain" and "plateau" to areas which are essentially flat or gently rolling with slopes up to 5°. These forms constitute major groups in a classification based solely on surface configuration.

OBJECTIONS TO DAVIS' USE OF "PLAINS" AND "PLATEAUS"

Specific criticisms which may be urged against Davis' use of "plains" and "plateaus" are as follows:

1. This use conflicts with current geographical, geological, and popular usage and has not taken hold except among a limited group of Davis', Johnson's, and Lobeck's students. While it is frequently desirable to restrict for scientific use the meanings of words popularly employed in a broad sense, it seems quite unjustifiable to use the words with an entirely different meaning. Moreover, there is need for the words "plain" and "plateau" in the description of topographic forms, just as there is need for the words "slope," "hilltop," "peak," "ridge," "spur," or "col."

2. The words "plain" and "plateau" carry within themselves no suggestion of geologic structure, although it was for this very purpose that they were used by Davis and his students. It is necessary to translate these terms into geologic language whenever they are used among persons other than geomorphologists. It would seem more reasonable to use, instead, the term "horizontal strata"[25] (or "flat-lying strata") for this structural class. The words "plain" and "plateau" may then be returned to the category of descriptive words used in connection with stage of development.

DISCUSSION OF THE CLASS "HORIZONTAL STRATA"

In urging the use of "horizontal strata" (or "flat-lying strata"), the writer is aware that strata are rarely, if

[22] *An Outline of Geography* (Boston: Ginn & Co., 1935), p. 66.

[23] *Elements of Geography* (New York: McGraw-Hill Book Co., 1936), pp. 317–427.

[24] *Asia's Lands and Peoples* (New York: McGraw-Hill Book Co., 1944), pp. 16–17.

[25] Pp. 44–72 of ftn. 17. This chapter provides a good example of the use of this term.

ever, precisely horizontal; but it is customary even to refer to the surfaces of water bodies as horizontal, although they are deformed by tidal forces, winds, or gravitational attraction of adjacent land masses. It is intended that strata be classed as horizontal as long as they give rise to a dominantly dendritic drainage pattern composed of insequent streams. In addition to sedimentary strata, extensive areas and thicknesses of flat-lying lavas are included, the expressions "horizontal lavas" or "horizontal flows" comprising convenient specific designation.

In classification and terminology, difficulty is likely to arise in regard to the structures intermediate between horizontal strata and distinctly folded, domed, or block-faulted strata. Extremely low dips give cuestas and subsequent lowlands with roughly trellis or rectangular drainage systems developed on a large scale, even though the greater proportion of the area is covered with a dendritic valley system. Often the larger pattern is detected only on small-scale maps and is not apparent when individual topographic quadrangles on the scale of 1:125,000 or larger are examined. Where inclination of strata has perceptible influence upon even the smaller elements of topography, the land mass may be termed "faintly inclined strata" or "gently folded strata," replacing such terms as "tilted or scarped plains," and "folded plains-plateaus." If the terms used are descriptive, no rigid system need be adhered to.

COASTAL PLAINS

From the foregoing discussion it might appear that some basis exists for finding a new term to replace "coastal plain" to designate extensive, recently emerged coastal belts underlain by appreciable thicknesses of seaward-sloping marine strata. Retention of "coastal plain" seems desirable for the following reasons: (1) The term is widely understood and is used in all branches of geology and geography. Introduction of a new term would serve no useful purpose while the old one is in good standing. (2) The term "coastal plain" is descriptive and does not violate accepted usage of the included words. Coastal plains have surfaces of low relief, not only in young and old stages, but often in maturity as well. Nevertheless, the term carries no information as to underlying structure and cannot be regarded as a fully satisfactory name for a structural class.

Coastal plains may be considered a class of equal importance with "horizontal strata" or a subclass under the latter. Lobeck treats coastal plains in a separate chapter and includes a discussion of ancient coastal plains of Paleozoic strata, but in his preliminary treatment of classification of land forms he makes no mention of coastal plains, thus implying that they do not comprise a separate class.[26]

MOUNTAINS

REVIEW OF USAGE

Davis[27] summarized as follows his classification of geologic structures for purposes of geomorphic description:

> It will suffice to recognize two great structural groups: first, the groups of horizontal structures, including plains, plateaus, and their derivatives, for which no single name has been suggested; second, the group of disordered structures, including mountains and their derivatives, likewise without a single name. The second group may be more elaborately subdivided than the first.

Although Davis later came to employ "plains and plateaus" and "mountains"

[26] Pp. 6–7, 14–15, 439–68, of ftn. 4 (1939).

[27] P. 482 of ftn. 1.

to designate these two groups, it is significant that he expressed some doubt or dissatisfaction with the nomenclature.

Douglas Johnson went still further than Davis in associating "mountains" with disturbed structures and dissociating the word entirely from its common meaning of bold-relief features. In the classroom he would designate any region of disturbed rocks as "mountains," even though it had been reduced to a peneplain. Johnson recognized four classes of mountains: folded mountains, dome mountains, block mountains, and complex mountains.

R. S. Tarr and L. Martin[28] followed Davis in restricting "mountains" to parts of the earth's crust which have been disturbed by diastrophic movement. They noted that "plateaus may be so dissected as to simulate rugged mountain topography, as in the Catskills, and mountains may be worn down to such low relief as to resemble a plain, as in the Piedmont Plateau." Here the difference between popular usage and Davis' terminology is evident.

Fenneman,[29] while adhering closely to Davis' use of "plain" and "plateau," has not always used "mountains" to signify structure alone. Thus in a tabular summary of physiographic divisions he has employed such expressions as "mountains of disordered crystalline rocks" and "mountains due to erosion of open folds," implying a distinction between the mountainous terrain and the rock structure beneath; but elsewhere in this paper he has simply used the terms "complex mountains," "block mountains," and "domed mountains." Lobeck[30] has followed the terminology developed by Johnson and employs the same four classes of mountains.

Despite the influence of Davis and his students, many geologists and geographers have continued to use "mountain" as it is defined by *Webster's New International Dictionary*,[31] namely, "any part of a land mass which projects conspicuously above its surroundings: in general, an elevation higher than a hill, with comparatively steep slopes, ... and relatively small summit area." This authority further adds that most mountains are produced by crustal deformation but sometimes result from erosion of plateaus.. Some random examples of this usage are noted below.

J. W. Powell[32] used "mountain" to signify a type of topography. From the wide variety of origins which he assigned to mountains it is clear that no structural implication was intended. R. D. Salisbury[33] treated as one of the major mountain groups those produced by the erosion of horizontal strata and cited as examples the Catskill Mountains in New York, the Timpanogas Mountains in Utah, and the Castle Group in Colorado. Other groups include volcanic mountains and mountains due to intrusion and uplift, folding, or faulting.

C. A. Cotton[34] has generally avoided Davis' usage and recognizes a distinction between mountains as relief features and disturbed structures which may underlie them. For example, he has used the heading "drainage of mountainous areas of folded rocks."

[28] *College Physiography* (New York: Macmillan Co., 1914), pp. 525–26.

[29] Pp. 274–79 of ftn. 13 (1928).

[30] Ftn. 4 (1939).

[31] Ftn. 15.

[32] Pp. 40–44 of ftn. 16.

[33] *Physiography* (New York: Henry Holt & Co., 1907), pp. 437–57.

[34] *Geomorphology of New Zealand* (Wellington, N.Z.: New Zealand Board of Science & Art, 1922), p. 85.

Longwell, Knopf, and Flint emphasize the close association of mountainous topography with disordered structures, but their use of "mountains" is clearly in a topographic meaning. As noted in the quotation cited earlier, these authors include regions of maturely dissected horizontal strata under the heading of "mountains." The usage is also clearly revealed by their reference to "a dome high enough to be a mountain."[35]

Among structural geologists, "mountains" seems to be used in the conventional manner. W. H. Bucher[36] rarely uses the term except in proper names. Instead, he employs descriptive terms emphasizing the nature of the deformation. M. P. Billings[37] likewise rarely refers to "mountains." One notable exception is "fault-block mountains," in which "the topography expresses the underlying structure more or less faithfully."

In most geography works examined by the writer, "mountains" refers to rugged topography. For example, Preston James[38] uses "mountain lands" to mean rugged terrain with sufficient relief to produce marked vertical zoning of vegetation. Finch and Trewartha[39] state that mountains are characterized by steep slopes, small summit areas, and strong relief. They distinguish mountains from other land forms on the basis of surface configuration. Cressey[40] uses a similar terminology and classification. Hills and mountains are distinguished from plains and plateaus on the basis of steepness of slopes, not on differences of lithology or structure.

Lobeck[41] has recently published a somewhat revised terminology for regions of disturbed geologic structures. It emphasizes the structures and restricts "mountains" to topographic forms of strong relief. The classes are entitled "dipping structures," "domes and basins," "block mountains," "folded structures," "complex structures," and "volcanoes." Thus for all except "block mountains" the word "mountains" has been dropped. His use of "plains" and "plateaus" for regions of horizontal strata remains unchanged.

OBJECTIONS TO DAVIS' USE OF "MOUNTAINS"

Specific criticisms of the use of "mountains" to signify land masses of disordered structure regardless of stage of erosion are as follows:

1. It conflicts with the generally accepted popular meaning of the word which has been used with little or no further qualification by the large majority of geographers and geologists. Confusion arises when the student of elementary geomorphology is told that the Piedmont Plateau is classified as "complex mountains"; that the broad Triassic lowlands of northern New Jersey are "block mountains" (or "folded mountains"); and that, on the other hand, towering peaks of the Uintas are in the group "plains and plateaus." A still more striking example might be the broad Hudson Valley lowland above Newburgh, classified as "folded mountains" by Davis, Johnson, and Lobeck. Adjacent to it are the rugged Catskill

[35] Pp. 295–318 of ftn. 21.

[36] *The Deformation of the Earth's Crust* (Princeton: Princeton University Press, 1933).

[37] *Structural Geology* (New York: Prentice-Hall, 1942), p. 195.

[38] Pp. 307–8 of ftn. 22.

[39] Pp. 443–71 of ftn. 23.

[40] Pp. 16–17 of ftn. 24.

[41] A. K. Lobeck and W. J. Tellington, *Military Maps and Air Photographs* (New York: McGraw-Hill Book Co., 1944), pp. 104–44.

Mountains, which they would classify, instead, as "plains and plateaus."

No good purpose is served by attempting to enforce a strange meaning of the word "mountains" upon persons who have always used it in a way acceptable to the best authorities. Because the old usage will not be abandoned by the vast majority, it would seem left to the followers of Davis and Johnson to choose between conformity or the perpetuation of a ceaseless struggle which only detracts from the true worth of Davis' basic principles of land-form evolution.

2. Application of the term "mountains" to all areas of appreciably folded, domed, or faulted strata imparts undeserved grandeur to structures of small size or limited deformation. For example, some areas of domed strata exhibit typical radial and annular drainage patterns, cuestas, and hogbacks, yet would scarcely qualify either as strongly deformed structures or as mountainous terrain. The Weald uplift in southeast England is treated by Lobeck in a chapter entitled "Dome Mountains," along with more apparent mountainous domes, such as the Black Hills.[42] Even the very broad gentle domes and basins of the interior eastern United States are included in this chapter, though they could scarcely be regarded as deformed structures.

PROPOSED MODIFICATION OF THE TERMINOLOGY OF DISTURBED STRUCTURES

A simple and effective modification of the terminology of disturbed structures as given by Davis, Johnson, and Lobeck may be had by omitting the word "mountains" wherever it appears. Thus "folded mountains" becomes "folds" or "folded strata"; "dome mountains" becomes "domes" or "domed strata"; "block mountains" becomes "fault blocks"; and "complex mountains" becomes "complex structures" or "complexly deformed rocks." The last class is discussed later and is stated to be in need of subdivision.

Advantages of these changes would be felt in two ways: (1) Words relating to topographic form are excluded and are reserved for discussions of topography produced in various stages of development in the cycle of erosion, while all words retained refer to rock structure; and (2) provision is made for inclusion of structures not sufficiently deformed or elevated to produce mountainous topography in any stage of their development.

Of the four classes of disturbed rocks, fault blocks and complex structures may be discussed further. The term "block mountains" has received unusually wide use, even by those who do not follow Johnson and Lobeck's system of terminology and classification, because mountain ranges normally result whenever tilted crustal blocks or horsts are greatly elevated. Nevertheless, the inadvisability of including the word "mountains" in the term has been expressed by other writers. Cotton prefers to restrict "block mountains" to actual mountain ranges carved from large uplifted earth blocks bounded on one or both sides by fault scarps.[43]

Marland Billings uses the terms "tilted fault block" and "horst" for structures which Davis, Johnson, or Lobeck would have classified as "block mountains."[44] Both Cotton and Billings recognize the need for a purely geological term which will include grabens, downtilted parts of fault blocks, and blocks only slightly faulted or tilted. In the

[42] Pp. 503–42 of ftn. 4 (1939).

[43] P. 151 of ftn. 34; *Geomorphology* (London: Whitcombe & Tombs, Ltd., 1942), pp. 154–61.

[44] P. 195 of ftn. 37.

judgment of the present writer, "block mountains" can be used as a convenient designation for actual mountain ranges produced by faulting but should not be applied to the structural class as a whole or to up-faulted blocks which have since been reduced to pediment or peneplain surfaces.

A possible additional structural class is suggested by the occurrence of sizable areas in which sedimentary strata are moderately to steeply inclined in one direction only. Most of these examples prove to be merely parts of much larger structural units whose form is not readily apparent within a limited area. For example, the dissected East Kaibab monocline in southern Utah appears as a broad belt of parallel ridges and valleys, in which all the strata dip eastward or northeastward. Although the monocline as a whole would perhaps be referred to the class "folds," a limited area might be classified "homoclinal strata." The same term could be applied to the belts of hogbacks and cuestas along the east base of the Colorado Front Range and to foothill belts of various ranges of the Rockies. While these may, in reality, be only limbs of great anticlinal folds, the exposure of broad belts of crystalline rocks along the center of the arches effectively separates the sedimentary limbs and makes desirable the designation "homoclinal strata" for each belt. Good examples of this are the small ranges flanking the Sweetwater arch in central Wyoming. Another example of homoclinal strata is in the Triassic Lowland of northern New Jersey. While the Triassic basin as a whole might be classed as "tilted fault blocks," areas the size of a 15-minute quadrangle may show fairly uniform westward dips, with no evidence of faulting and no means of ascertaining whether the gross structure is a large tilted fault block or a large fold. In view of these considerations there seems to be a good case for use of the term "homoclinal strata"; but, because such areas are usually, if not always, parts of larger structures, the term would logically refer to subclasses under "folds," "domes," and "fault blocks."

The class "complex mountains," as employed by Johnson and Lobeck, includes a great variety of structures and resultant land forms, some of which differ among themselves, both in structure and in topography, to an even greater extent than do certain of the other major classes of disturbed structures. Johnson made a classroom practice of including in "complex mountains" all intrusive and metamorphic rocks, as well as any combinations of other structures which do not show distinctive and simple relief forms. The wide variety in types has been fully recognized by Lobeck, who subdivides the class "complex mountains" into (1) igneous areas, (2) metamorphic areas, and (3) strongly disturbed sedimentary areas.[45] The present writer would, however, suggest a somewhat different grouping, as follows:

1. *Homogeneous crystallines.*—Included here are land masses composed of massive intrusive rocks or "plutons,"[46] and metamorphic rocks, principally schists and gneisses, whose composition is essentially homogeneous throughout and results in dendritic drainage development. Furthermore, because such a mass is anything but complex in its behavior to denudational processes, it should not be retained in the class of complex structures but should be given the rank of a major structural class.

Areas of homogeneous crystalline rocks are widespread. Examples may be

[45] Pp. 624–25 of ftn. 4 (1939).

[46] P. 261 of ftn. 37.

found in the southern Idaho[47] and the Piedmont.[48] Two unusually striking examples of uniform dendritic drainage pattern and slopes may be cited. In the area of the Mount Gleason, California, Quadrangle map (1:24,000), this topography is developed on anorthosites, diorites, and granodiorites of the San Gabriel Mountains block.[49] On the Dome Rock Mountains, Arizona, Quadrangle map (1:62,500) is shown a fine-textured dendritic topography developed on Archean (?) schists, gneisses, or granites.[50] A few of the larger valleys are rectilinear and trend northwest-southeast, suggesting fault zones, but the areas referred to lie between these zones. Where homogeneous masses are faulted or strongly jointed, as in the Elizabethtown, New York, Quadrangle or Yosemite National Park, the terms "faulted homogeneous crystallines" or "strongly jointed homogeneous crystallines" may be employed.

2. *Belted metamorphics*—Included in this group are areas of metamorphosed sedimentary and igneous rocks, folded and faulted in such a manner as to give distinct, but irregular, elongate, subparallel ridges and valleys resulting from the etching-out of weaker limestones or schists from between bands of quartzites, gneisses, or younger linear intrusions. Examples may be found in the New Jersey and Hudson Highlands (Schunemunk and Ramapo, New York, quadrangles) and in parts of the Blue Ridge and Piedmont provinces (Antietam, Maryland, Virginia, West Virginia, and Westminister, Maryland, quadrangles).

3. *Complexly deformed or intruded rocks.*—In this group would be placed all masses of highly complex structure and lithology which give rise to great irregularity of topographic expression. Here one or more periods of folding, faulting, and intrusion may have occurred. The topography may show hills or mountain masses varying locally in height, shape, and trend and in steepness of slopes. Drainage patterns may be irregular and not resolvable into any one of the systematic patterns characteristic of the other constructional land forms. Under such circumstances, map interpretation of structure and lithology is extremely difficult, if not impossible. Good examples may be found in New England (Averill, Vermont, New Hampshire, Quadrangle and Winnepesauke, New Hampshire, Quadrangle), in the northern Rockies (Silvertip, Montana, Quadrangle), in the Black Hills (Deadwood and Harney Peak, South Dakota, quadrangles), and in central Arizona (Bradshaw Mountains Quadrangle).

The three types described above are not always clearly distinguishable, and intermediate types are numerous; but the fact that gradations may occur in nature does not justify lumping together distinctive types under the older term "complex mountains." Gradations likewise occur between regions of horizontal strata and those of folds, domes, and fault blocks, but this fact has not prevented the use of separate structural classes. The significant point brought

[47] Maps of the Sawtooth and Yellow Pine Quadrangles (U.S. Geol. Surv.) illustrate topography typical of the Idaho batholith. The Sawtooth map, 1:125,000, is old and generalized. The Yellow Pine map, 1:62,500, is recent and detailed. Glaciation, which produced numerous cirques and troughs, has destroyed much of the uniformity of slopes and drainage pattern.

[48] The Columbia, S.C., Quadrangle, 1:125,000 (U.S. Geol. Surv.) map shows topography produced on granite, which underlies much of the Piedmont from Virginia to Georgia.

[49] William J. Miller, "Geology of the Western San Gabriel Mountains of California," *Univ. Calif. Pub. Math. Phys. Sci.*, Vol. I (1934), pp. 1–114.

[50] N. H. Darton *et. al.*, "Geologic Map of Arizona," *Ariz. Bur. Mines and U.S. Geol. Surv.* (1924).

forward here is the need for recognition of homogeneous bodies of igneous and metamorphic rock as comprising a relatively simple kind of land mass to be distinguished from those of genuinely complex structure and topography.

TABULATION AND CONCLUSIONS

In Table 1 is shown a comparison between the terminology originated by Davis and developed further by Johnson and Lobeck, and the modified terminology proposed by the writer.

TABLE 1

COMPARISON OF TERMINOLOGIES USED IN CLASSIFICATION OF LAND MASSES

Classification Based on Initial Land Forms (Davis, Johnson, and Lobeck)	Classification Based on Geologic Structure (Strahler)
1. Plains-plateaus	1. Undisturbed structures
a) Interior plains *b*) Plateaus *c*) Coastal plains	*a*) Horizontal strata (or flat-lying strata) *b*) Coastal plains
2. Mountains	2. Disturbed structures
a) Folded mountains	*a*) Folds
b) Dome mountains	*b*) Domes
c) Block mountains	*c*) Fault blocks
d) Complex mountains	*d*) Homogeneous crystallines
1) Igneous areas	*e*) Belted metamorphics
2) Metamorphic areas	*f*) Complexly deformed or intruded rocks
3) Strongly disturbed sedimentary areas	
3. Volcanoes and related forms	3. Volcanoes and related forms

Whereas the older terminology referred to the initial land forms produced by diastrophism and vulcanism and could not properly be applied either to the sequential land forms or to the underlying rock structures, the newer terminology clearly classifies regions according to their geologic structure. The "constructional" or "initial" land forms should be treated as features of a stage in the erosion cycle and not identified with geologic structures. Confusion seems to have followed from the attempt to make the term "land form," which refers to surface configuration, synonymous with "structure," which refers to subsurface conditions.

The proposed revision of terminology employs no newly coined words and does not alter the genetic classification of initial and sequential land forms built up by Davis, Johnson, and Lobeck. With the exception of "coastal plain," all terms refer to geologic structure or lithology rather than to topography, thereby rendering the terminology consistent with Davis' first element of the geomorphic triad—structure, process, and stage—and reserving topographic terms for the third element.

The revision results in removal of words which have not been generally accepted with the special definitions imposed upon them and which have tended to cause confusion among students of elementary geomorphology, as well as among workers in other fields of geology and in geography. Although the abandonment of Davis' usage of certain terms is proposed, it is hoped that the understanding and application of his explanatory system of land-form description will instead be facilitated.

CORRELATION BETWEEN FISH DISTRIBUTION AND PLEISTOCENE HYDROGRAPHY IN EASTERN CALIFORNIA AND SOUTHWESTERN NEVADA, WITH A MAP OF THE PLEISTOCENE WATERS[1]

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ABSTRACT

During late Pleistocene time an integrated river system occupied several of the desert basins in eastern California and southwestern Nevada, with Death Valley as the sump. A study of the Recent and fossil fishes of the region supports the physiographic evidence for the existence of this drainage and presents zoögeographic data which strongly suggest connections between this system and the Lahontan basin to the north, as well as with the Colorado River basin to the south and east. Both the physiographic and the fish evidence harmonize. Detailed maps of the Pleistocene and Recent hydrography of the southern Great Basin are presented, and two new lakes are mapped and named.

INTRODUCTION

For more than half a century geologists have studied and described Pleistocene lakes and drainage systems from the arid region of the western United States. Information regarding the best known of these former bodies of water, Lake Bonneville[2] and Lake Lahontan,[3] is based on extensive physiographic data, and their history is known in comparatively great detail. Knowledge concerning the considerable number of lesser lakes,[4] which were more or less contemporaneous with Bonneville and Lahontan, is much more fragmentary and calls for renewed investigation.

At some time during the Pleistocene epoch nearly all the enclosed basins in the West probably held lakes of varying size and duration. Only a very few of these basins have received the careful study which they deserve, and, in general, only the more recent history is at all clear. One can seldom do more than speculate on the conditions which may have prevailed in middle or early Pleistocene times.

DEATH VALLEY SYSTEM

There is unmistakable physiographic evidence that during the latter part of Pleistocene time an integrated river system existed in eastern California and adjoining parts of Nevada (Fig. 1). I have named this drainage the "Death Valley system"[5] because the Death Valley trough formed the sump for its waters. From this terminus the tributaries spread out in all directions to drain an area nearly one-fifth that of the state of California (Fig. 2, insert). The detailed history of this river system appears to have been very complicated, and much of the story remains to be deciphered.

The late physiographic history of the

[1] Excerpt from a dissertation submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the University of Michigan. Published by permission of the Secretary of the Smithsonian Institution.

[2] Grove Karl Gilbert, "Lake Bonneville," *U.S. Geol. Surv. Mono. 1* (1890). Pp. i–xx+1–438; Figs. 1–51; Pls. 1–51; 1 map.

[3] Israel Cook Russell, "Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada," *U.S. Geol. Surv. Mono. 11* (1885). Pp. i–xiv+1–288; Figs. 1–35*a–c*; Pls. 1–46.

[4] Oscar E. Meinzer, "Map of the Pleistocene Lakes of the Basin-and-Range Province and Its Significance," *Bull. Geol Soc. Amer.*, Vol. XXXIII (1922), pp. 541–52, Figs. 1–4.

[5] Robert R. Miller, "*Cyprinodon salinus*, a New Species of Fish from Death Valley, California," *Copeia*, No. 2 (1943), p. 69.

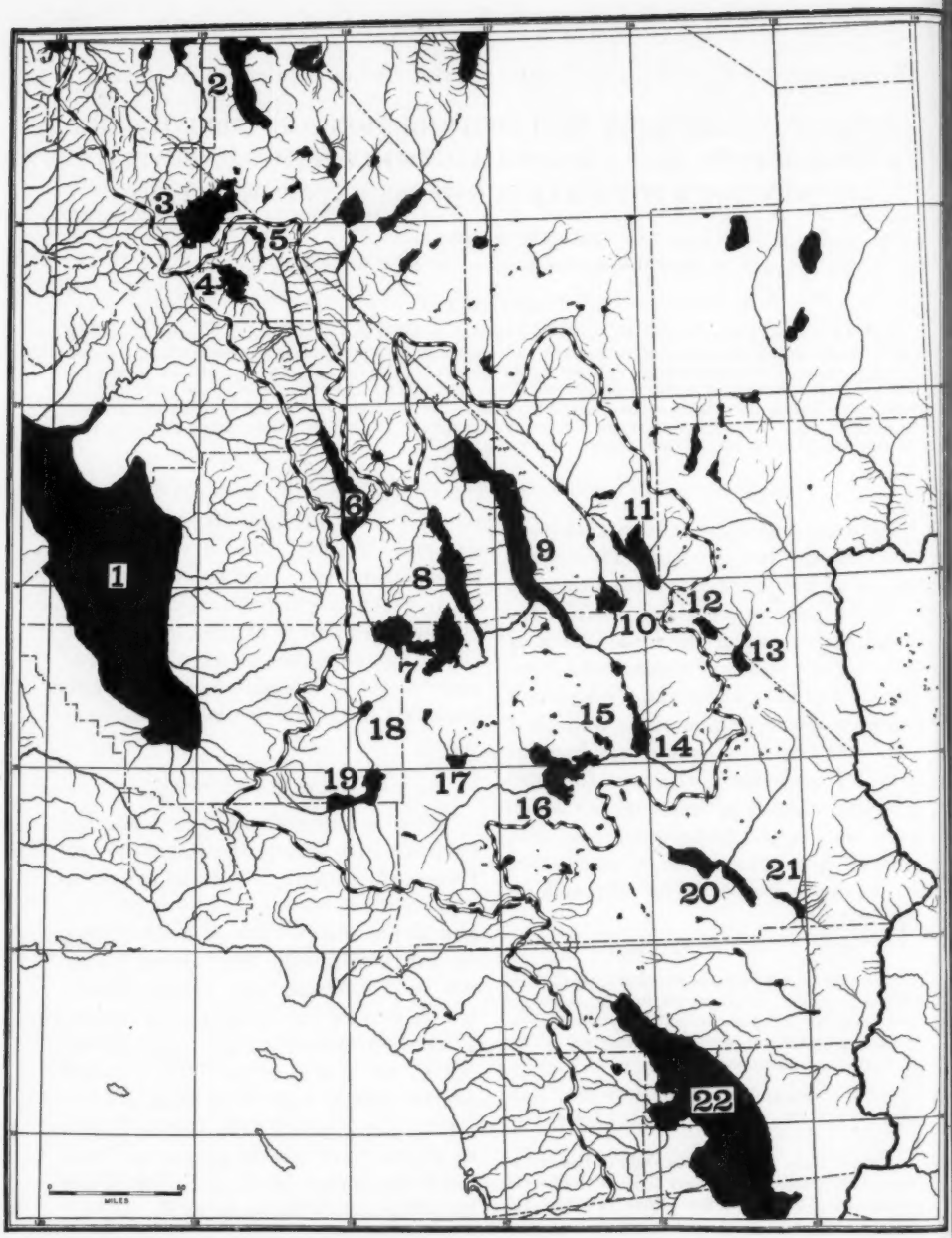

FIG. 1.—Maximum extent of the Pleistocene waters of the southern Great Basin and adjacent areas. The wider boundary line marks the separation between coastal and interior or Colorado River drainages. The narrower line indicates the outline of the Death Valley system (see insert, Fig. 2). Modified after U.S. Geological Survey maps of California and Nevada.

rivers and lakes in this area is divisible into at least two stages, which E. Blackwelder[6] has tentatively correlated with the Tahoe and Tioga stages of glaciation in the near-by Sierra Nevadas. These stages, in turn, are believed to have been approximately contemporaneous with the earliest and latest stages of the Wisconsin or last continental glaciation of eastern North America.[7] Still earlier phases also seem to be represented.

It has been established by H. S. Gale[8] and Blackwelder[9] that Owens River was formerly tributary to Death Valley

[6] Eliot Blackwelder, "Pleistocene Glaciation in the Sierra Nevada and Basin Ranges," *Bull. Geol. Soc. Amer.*, Vol. XLII (1931), p. 918.

[7] "Lake Manly: An Extinct Lake of Death Valley," *Geog. Rev.*, Vol. XXIII (1933), pp. 464–71, Figs. 1–4; "Pleistocene Lake Tecopa," *Pan-Amer. Geol.*, Vol. LXIII (1936), p. 311.

[8] "Salines in the Owens, Searles, and Panamint Basins, Southeastern California," *U.S. Geol. Surv. Bull. 580-L* (1914), pp. i–vi and 251–323, Figs. 58–88, Pls. 5–7.

[9] Ftn. 6 (1933).

KEY TO FIGURE 1

Pleistocene Lake	Authorities
1. Lake Tulare	Blake (1857) (*Pacific Railroad Expl. and Surv.*, Vol. V (1856); last map at end of geological report)
2. Walker Lake arm of Lake Lahontan	Russell (1885)
3. Lake Mono	Russell (1889)*
4. Lake Long Valley	Mayo (1934)* (*Science*, Vol. LXXX [new ser.], pp. 95–96); Jenkins (1938) (Geologic Map of California; *Calif. Dept. Nat. Res., Div. Mines*); original observations
5. Lake Adobe†	Original observations (1938, 1942)
6. Lake Owens	Gale (1914)*; Jenkins (1938)
7. Lake Searles	Gale (1914)*
8. Lake Panamint	Gale (1914)*
9. Lake Manly	Blackwelder (1933)*
10. Lake Tecopa	Noble (1931) (*U.S. Geol. Surv. Bull. 820*, pp. 64–68, Pl. 11*A*); Thompson (1929), Pl. 8; Blackwelder (1936)*; Jenkins (1938); original observations
11. Lake Pahrump	Waring (1920); original observations (see text)
12. Lake Mesquite	Jenkins (1938)
13. Lake Ivanpah	Waring (1920); Jenkins (1938)
14. Lake Mohave	Thompson (1921)* (*Jour. Wash. Acad. Sci.*, Vol. XI, pp. 423–24), (1929); Bode (1935) (*Southwest Mus. Papers*, Vol. XI, pp. 108–18)
15. Little Lake Mohave	Thompson (1921,* 1929); Jenkins (1938); original observations
16. Lake Manix	Buwalda (1914)* (*Bull. Univ. Calif. Dept. Geol.*, Vol. VII, pp. 443–64); Blackwelder and Ellsworth (1936); Jenkins (1938); original observations
17. Lake Harper	Jenkins (1938)
18. Lake Kane	Thompson (1929), Pl. 8
19. Lake Thompson‡	Thompson (1929); Jenkins (1938)
20. Lake Amboy	Thompson (1929)*; Jenkins (1938)
21. Lake Ward	Thompson (1929)*; Jenkins (1938)
22. Lake Cahuilla	Blake (1907)* (*Nat. Geog. Mag.*, Vol. XVIII, p. 830); U.S. Geol. Surv., Salton Sink quadrangle; Mexican portion after Sykes (1937) (*Carnegie Inst. Wash., Pub. 460*, Pl. 1), modified by Rogers (1939) (*San Diego Mus. Papers*, Vol. III, Map 1)

* The asterisks denote the authors who proposed definite names for ancient lakes.

† Name proposed from the name of the valley occupied by the Pleistocene lake.

‡ It is proposed that this Pleistocene lake be named in honor of the late David Grosh Thompson, who carried out extensive studies on the ancient lakes of the Mohave Desert region.

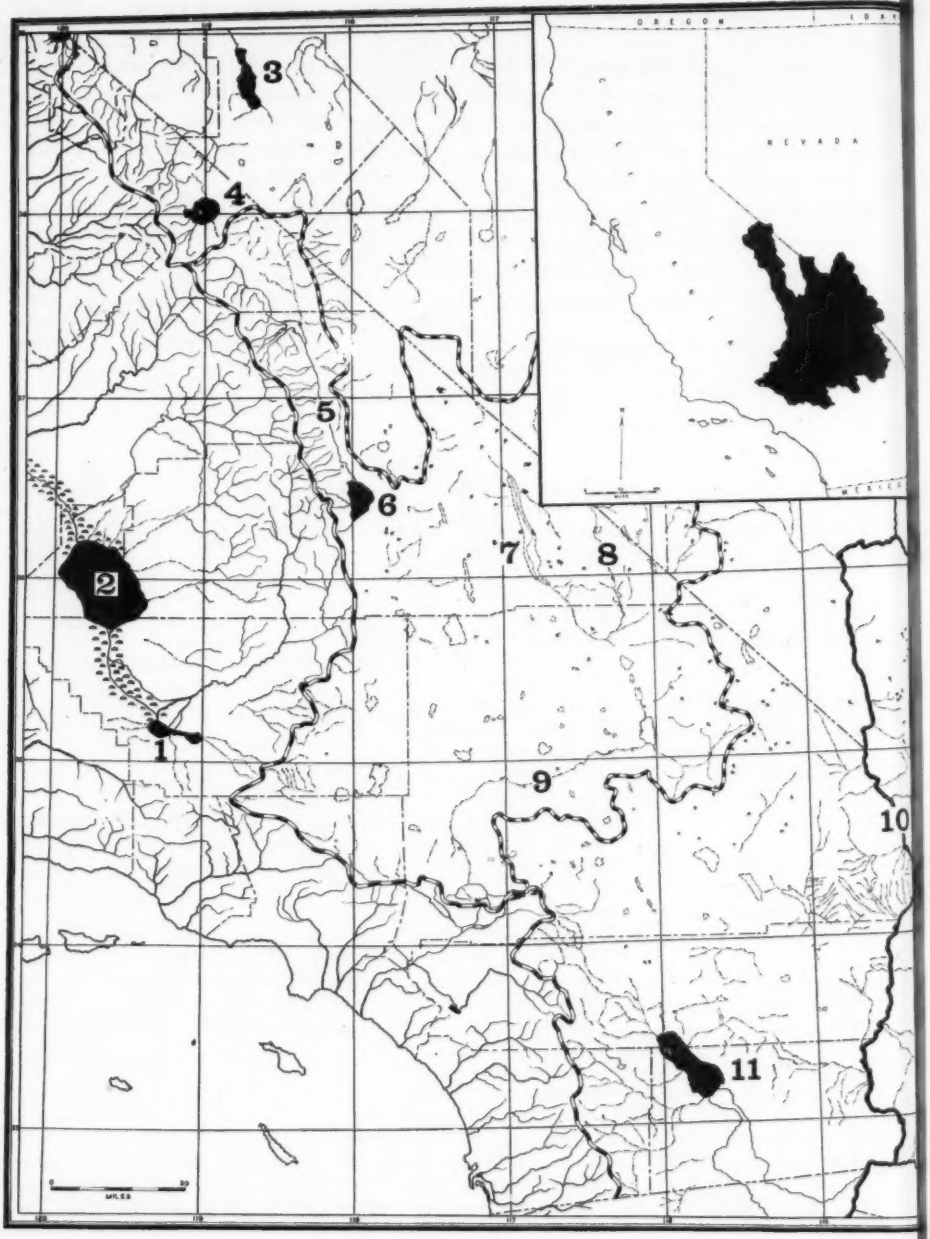

FIG. 2.—Recent hydrography of the southern Great Basin and adjacent areas. The wider boundary line d the separation between coastal and interior or Colorado River drainages. The narrower line indicates the outline o Death Valley system (see insert). For comparison with the Pleistocene waters see Figure 1. In the area blocke by the insert there are no Recent lakes.

through a chain of lakes beginning with the basin of Owens Lake and ending in Death Valley (Fig. 1). Owens River filled Lake Owens[10] to overflowing and continued southward and eastward to the basins of Lake China and Lake Searles. At maximum extent,[11] Lake Searles covered both of these basins and was about 640 feet deep. At a later stage[12] both Lake China and Lake Searles were separate bodies connected by a channel through Salt Wells Valley. During the higher stage, Lake Searles overflowed at the southeastern end to fill Panamint Valley and form Lake Panamint, a narrow body of water 60 miles long and over 900 feet deep. It is believed that at its greatest height Lake Panamint discharged into Lake Manly, the terminal lake of the series in Death Valley (Fig. 1, No. 9). This body of water was about 100 miles long and 600 feet deep.[13] At the same time that waters poured into Lake Manly from Owens Valley, Death Valley probably received the discharge of both the Amargosa and Mohave rivers, whose conjoined waters entered from the south.

During this period, tentatively correlated by Blackwelder with the Tahoe glacial stage, a continuous waterway probably connected Owens Valley with the Amargosa and Mohave river basins. It was therefore possible for fish life to move between those now isolated drainages.

In addition to the present catchment area of the Amargosa River basin, there are both physiographic data and fish evidence (discussed below) to support the view that Pahrump Valley, along the California-Nevada boundary (Fig. 1, No. 11), filled and discharged into the Amargosa River. Similarly, a Pleistocene lake filled Adobe Valley (Fig. 1, No. 5), and its waters rose to cut an impressive outlet into the now virtually dry North Fork of Owens River.

CORRELATION BETWEEN FISH DISTRIBUTION AND HYDROGRAPHY

A systematic study of the Recent and fossil fish fauna of the Death Valley system[14] presents evidence which has a definite bearing on physiographic conclusions regarding the Pleistocene hydrography of this region. These data not only demonstrate the former continuity of the drainage but strongly favor the view

[10] In this account the name of the Pleistocene lake follows the word "Lake," whereas the name used for the Recent body of water precedes the word "Lake."

[11] Gale, Pl. 7 in ftn. 8.

[12] Eliot Blackwelder, "Lakes of Two Ages in Searles Basin, California," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1943–44.

[13] L. F. Noble, "Note on a Colemanite Deposit near Shoshone, Calif., with a Sketch of the Geology of a Part of Amargosa Valley," *U.S. Geol. Surv. Bull. 785* (1926), pp. 63–75, Fig. 14; Blackwelder, ftn. 6 (1933).

[14] Robert R. Miller, "The Fishes of the Relict Waters of the Pleistocene Death Valley Stream System" (typewritten Doctorate dissertation, University of Michigan, 1944), pp. i–v + 1–326, Figs. 1–33, Pls. 1–22, Maps 1–6; "Four New Species of Fossil Cyprinodont Fishes from Eastern California," *Jour. Wash. Acad. Sci.*, Vol. XXXV (1945), pp. 315–21, Figs. 1–4.

KEY TO FIGURE 2

1. Kern and Buena Vista Lakes
2. Tulare Lake
3. Walker Lake
4. Mono Lake
5. Owens River
6. Owens Lake
7. Death Valley
8. Amargosa River
9. Mohave River
10. Colorado River
11. Salton Sea

Kern, Buena Vista, and Tulare lakes are mapped as they existed in 1876. These lakes are now dry basins.

that the Death Valley system, or a preceding drainage of even greater extent, had connections with the Lahontan basin to the north as well as with the Colorado basin to the east. Let us examine the evidence.

Cyprinodon, a genus of small fishes of the family Cyprinodontidae found in temperate and tropical fresh, brackish, and salt waters, is present in the system in Owens Valley, Death Valley, and the middle and lower Amargosa River basin. Its absence from the Mohave River is attributed to the lack of a suitable habitat. It is elsewhere known in the West only from the lower Colorado River basin,[15] and the species of that drainage obviously was derived from relatives to the east where the genus reaches its maximum development. The conclusions drawn are that (1) the occurrence of *Cyprinodon* in the Death Valley system demands that a connection once existed between that drainage and the Colorado River basin and (2) the now isolated basins of Owens Valley, Death Valley, and the Amargosa River were once united by waterways. The discovery of a fossil *Cyprinodon* in Death Valley, in beds of late Tertiary or early Quaternary age, indicates that the connection with the Colorado was an ancient one.

The presence of the minnow *Siphateles* in the Death Valley system is also highly significant in an interpretation of past hydrography. *Siphateles* is unknown from the Colorado River basin, either as a Recent or as a fossil member, but is abundantly represented in the Lahontan basin and other systems to the north and west.[16] In the Death Valley system it inhabits only Mohave and Owens rivers, and fossils referred to this genus have been found in Pleistocene lake beds of those two drainages.[17] Again we can conclude that (1) the Death Valley system was connected at one time with the Lahontan basin of western Nevada and (2) the now widely separated Owens and Mohave rivers were united by a waterway at some time during the Pleistocene epoch.

Empetrichthys, another cyprinodont fish, is confined to the Death Valley system, where it is known only from Pahrump Valley, an isolated basin, and Ash Meadows, of the Amargosa River drainage. Both of these localities lie in extreme southern Nye County, Nevada, and are separated by a rather low, alluvial divide.[18] E. E. Free[19] indicated that Pahrump Valley was tributary to the Amargosa River during the existence of Lake Lahontan. As far as I am aware, no evidence has been presented to prove or disprove his contention, but he made several erroneous claims for connections of other desert basins in that period.[20]

[15] Robert R. Miller, "The Status of *Cyprinodon macularius* and *Cyprinodon nevadensis*, Two Desert Fishes of Western North America," *Univ. Mich., Mus. Zoöl., Occasional Papers, No. 473* (1943), pp. 1–25, Fig. 1, Pls. 1–7.

[16] John Otterbein Snyder, "The Relationships of the Fish Fauna of the Lakes of Southeastern Oregon," *Bull. U.S. Bur. Fish.* [1907], Vol. XXVII (1908), pp. 78, 86–97, Figs. 3–4; "The Fishes of the Lahontan System of Nevada and Northeastern California," *Bull. U.S. Bur. Fish.* [1915]; Vol. XXXV (1917), pp. 60–67.

[17] Eliot Blackwelder and Elmer W. Ellsworth, "Pleistocene Lakes of the Afton Basin, California," *Amer. Jour. Sci.*, Vol. XXXI (1936), pp. 453–63, Figs. 1–4; Miller, pp. 91–93 of ftn. 14 (1944).

[18] Gerald A. Waring, "Ground Water in Pahrump Mesquite, and Ivanpah Valleys, Nevada and California," *U.S. Geol. Surv. Water-Supply Paper 450* (1920), Pl. 8.

[19] "The Topographical Features of the Desert Basins of the United States with Reference to the Possible Occurrence of Potash," *U.S. Dept. Agric. Bull. 54* (1914), pp. 43–44.

[20] Carl L. Hubbs and Robert R. Miller, "The Fish Faunas of the Desert Basins of the Western

That a waterway connected Pahrump Valley and the Amargosa basin during Pleistocene time seems very likely from both physiographic and zoögeographic evidence. The elevation of the lake-bed remnants of Lake Pahrump,[21] near the Pahrump Ranch, is about 50 feet higher than that of the lowest divide between Pahrump Valley and the Amargosa basin.[22] The elevated position of the beds is attributable to the known tilting and faulting which have taken place since their deposition. The presence of *Empetrichthys* in the two basins supports the physiographic conclusion that they were once part of a common drainage.

One other fish—a sucker of the genus *Catostomus*—presents further, though less convincing, evidence in favor of the view that the Lahontan and Death Valley systems were once united. This fish, confined to the Owens River basin, very probably was derived from *Catostomus tahoensis*, its nearest relative, which occurs in the Lahontan basin. Although the genus is represented in the lower Colorado River by *C. latipinnis*, the relationships of the Recent species argue against a belief that the Owens River sucker was derived from an ancestral Colorado River form rather than from one in the Lahontan basin. The late Dr. J. O. Snyder believed that all the fishes inhabiting Owens Valley, except *Cyprinodon*, were identical with species in the Lahontan basin.[23]

Presumably the ancestral sucker and minnow (*Siphateles*) moved southward from the Lahontan basin into Owens Valley by way of the Mono basin during or before the existence of Pleistocene Lake Mono (Fig. 1, No. 3), at a time prior to the formation of the Mono Craters. Although I. C. Russell[24] found no evidence that the Mono and Lahontan basins were connected during the existence of Lake Mono, it is quite likely, as he hinted, that a waterway was established between these basins during an earlier stage by way of what are now the East Fork of the Walker River and Aurora Valley.[25] After fish life entered the Mono basin, a hydrographic connection probably was established with the headwater region of Owens River in Long Valley, and the species spread southward. Dr. W. C. Putnam, of the University of California at Los Angeles, who has investigated the region, wrote[26] that he believes there is good physiographic evidence for such a connection. At a later date the Mono Craters were formed, blocking this drainage and perhaps destroying the fish fauna of the Mono basin by a deluge of volcanic ash. Such a hypothesis could explain why this basin is now devoid of native fishes and is similar to the hypothesis advanced by D. S. Jordan[27] to explain the destruction of fish and other life on the Yellowstone plateau.

Preliminary study of one other minnow of the genus *Rhinichthys* in the

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United States, Correlated with Recent and Pleistocene Hydrography," in: "The Great Basin, with Emphasis on Glacial and Postglacial Times" (unpublished manuscript).

[21] It is proposed that "Lake Pahrump" (roughly mapped herein as Fig. 1, No. 11) be the name of the Pleistocene body of water which formerly filled a large part of Pahrump Valley.

[22] Ftn. 18.

[23] "An Account of Some Fishes from Owens River, California," *Proc. U.S. Nat. Mus.*, Vol. LIV (1917), pp. 201–5.

[24] "Quaternary History of Mono Valley, California," *U.S. Geol. Surv. 8th Ann. Rept.* (1886–87), Part I (1889), pp. 300–301.

[25] Aurora Valley contained a shallow Pleistocene lake shown on Fig. 1 near the upper end of Lake Mono (No. 3).

[26] Personal communication.

[27] "A Reconnoissance of the Streams and Lakes of the Yellowstone National Park, Wyoming, in the Interest of the United States Fish Commission," *Bull. U.S. Fish Com.* [1889], Vol. IX (1891), p. 43.

Death Valley system tends to support another hypothetical waterway which, by stream capture, may have transferred fish of this genus from a tributary of the Colorado into the Amargosa River, now a flood tributary of Death Valley. *Rhinichthys* is found in the Death Valley system only in Owens Valley and the Amargosa River. Its absence from the headwaters of the Mohave River is an enigma, which may be solved when more details of the Pleistocene hydrography are known. Although the evidence is not conclusive, because the problem has not been fully studied, it is very likely that the ancestral Amargosa River stock did not come from Owens River (which almost surely received its stock from the Lahontan basin) but from the Colorado River basin. A *Rhinichthys* is known from Las Vegas Creek, a flood tributary of the Colorado, and the form inhabiting the Amargosa River may have been derived from an ancestral type which was once more widespread in the Las Vegas region. James Gilluly[28] described physiographic evidence for a connection across the alluvial divide separating the Las Vegas and the Amargosa basins. An area of some 150 square miles between Charleston and Point of Rocks in Nevada (see U.S. Geol. Surv., Las Vegas and Furnace Creek quadrangles) was formerly tributary to Indian Springs Valley but has been captured by a tributary of Amargosa River. Indian Springs Valley, a northwestern extension of the Las Vegas trough, formerly held a lake [29] which presumably had no outlet at the stage described by Carpenter but which may have had an earlier (mid-Pleistocene?) discharge south and east to the Colorado River or its antecedent.[30] That *Cyprinodon* also entered the Death Valley system by this route is most unlikely, as this genus is not adapted for life in the current and never seeks the higher tributaries.

WATERWAY BETWEEN DEATH VALLEY AND THE COLORADO RIVER BASIN

A hydrographic connection between Death Valley and the Colorado River already has been suggested by geologists.[31] A series of troughs extending southward and eastward from Death Valley may represent the route along which such a connection once existed. In geographic sequence these troughs are: the Soda–Silver Lake basin, which was occupied by Pleistocene Lake Mohave (Fig. 1, No. 14); the Ludlow basin just to the south; the Bristol-Cadiz basin, the site of Pleistocene Lake Amboy (Fig. 1, No. 20); then either an adjacent, unnamed basin to the south or Danby basin, Pleistocene Lake Ward (Fig. 1, No. 21), to the east. If a drainage ever followed this line of troughs, the physiographic evidence has been erased by subsequent erosion, regrading, and vulcanism. Blackwelder and Ellsworth[32] hypothesized that an immense Pleistocene lake filled Death Valley and the trough to the south, finally overflowing into the Bristol-Cadiz-Danby trough east of Ludlow, and that from there the waters continued to the Colorado River. There is no concrete evidence that such a lake or outlet channel ever existed; but, when it is realized that the

[28] "Possible Desert-Basin Integration in Utah," *Jour. Geol.*, Vol. XXXVII (1929), p. 682.

[29] Everett Carpenter, "Ground Water in Southeastern Nevada," *U.S. Geol. Surv. Water-Supply Paper 365* (1915), p. 72, Pl. 1. On Fig. 1, this lake is the largest one northward of No. 11.

[30] Hubbs and Miller, ftn. 20.

[31] Blackwelder, ftn. 6 (1933); Eliot Blackwelder, "Origin of the Colorado River," *Bull. Geol. Soc. Amer.*, Vol. XLV (1934), p. 562; Blackwelder and Ellsworth, ftn. 17.

[32] Ftn. 17.

Grand Canyon probably has been cut since mid-Pleistocene time, it is not difficult to understand how the evidence for such a connection might have been completely erased.

There is also the possibility that the Mohave River had a temporary connection with the Colorado while maintaining a normal discharge toward Death Valley. Such a drainage relationship, on a very small scale, is effected at the present time when, at its mouth near Baxter, the Mohave alternately discharges northward into Cronese basin (remnant of Pleistocene Little Lake Mohave) and then eastward into Soda Lake basin (Pleistocene Lake Mohave). Before Lake Manix (Fig. 1, No. 16) was drained, Mohave River stood at a much higher level in the outlet channel (which is now Afton Canyon) and could have discharged, temporarily at least, alternately eastward (into the basin of Lake Mohave) and south-southeastward toward Ludlow. The divide between the basin of Soda Lake and Ludlow is alluvial and low, and the divide between Ludlow and Amboy, of rather recent lava,[33] may have been low enough at that time to have been topped by the flooding waters.

It may even be suggested that the Mohave River formerly followed a course south of its present one along a line connecting Barstow and Ludlow and continuing eastward to the Colorado River. The divide west of Ludlow is only 75 feet higher than at Ash Hill, east of Ludlow. Thompson,[34] in describing the valley in which Ludlow is situated, wrote: "It is possible that the great Barstow-Bristol trough, whether it is an erosion valley or a fault trough, is older than the Tertiary Lavas." The vulcanism which occurred during Pleistocene time may have altered the course of Mohave River, forcing it to fill the large basin east of Barstow to form Lake Manix. Since the lowest rim of this lake lay at the northeast, Mohave River cut for itself a new course, which it has followed since.

Moreover, N. H. Darton and others[35] wrote of the Bristol-Cadiz trough: "The origin of this basin has not been fully ascertained, but as the depression is completely surrounded by a rock rim it cannot be due entirely to erosion and probably has resulted from tilting of a portion of an old stream valley." Also Thompson,[36] in writing of this trough, said: "Between Ash Hill and Klondike, north of the railway, two wide washes from 20 to 40 feet deep come from the hills on the north. These washes are so much larger than the washes elsewhere on the alluvial slopes in the valley that a question arises as to their origin." Ash Hill is the volcanic divide separating the Ludlow and Bristol-Cadiz basins. According to free,[37] who postulated late Pleistocene connections with abandon, the Bristol-Cadiz and Danby basins drained to the Colorado River during Lahontan time.

In a recent paper[38] the minnow *Gila orcuttii* was regarded as native to the Mohave River. If this should be true, it would have an important bearing on a hydrographic connection between Pleistocene Mohave River and the Colorado

[33] David G. Thompson, "The Mohave Desert Region, California," *U.S. Geol. Surv. Water-Supply Paper 578* (1929), p. 660.

[34] *Ibid.*, p. 658.

[35] "Guidebook of the Western United States. Part C. The Santa Fe Route, with a Side Trip to the Grand Canyon of the Colorado," *U.S. Geol. Surv. Bull. 613* (1915), p. 153.

[36] P. 694 of ftn. 33.

[37] P. 46 of ftn. 19.

[38] Carl L. Hubbs and Robert R. Miller, "Mass Hybridization between Two Genera of Cyprinid Fishes in the Mohave Desert, California," *Papers Mich. Acad. Sci., Arts, and Letters* [1942], Vol. XXVIII (1943), pp. 347–48, 376.

River basin, for the genus is well represented in the Colorado fauna and the ancestral stock of *orcuttii* was presumably derived from that basin. However, new data and information now make it seem virtually certain that *G. orcuttii* was recently introduced into Mohave River.[39]

In summary, the theoretical evidence for a once continuous water course between Death Valley and the lower Colorado River basin is good. Structural troughs occur along the hypothetical outlet. Death Valley received water from nearly the entire eastern face of the rugged Sierra Nevada Range, the extensive Amargosa River drainage basin, and the well-watered headwater area of Mohave River, as well as other minor drainages, and presumably the inflow was in excess of evaporation, so that the basin was filled to overflowing. The most logical route for such an overflow was south and east to the lower Colorado River. Mohave River may have alternately discharged into the Death Valley lake and toward the Colorado River, or it may have once directly connected with the Colorado River through a series of lakes east of Barstow. The occurrence of *Cyprinodon* in the Death Valley system demands a connection with the basin of the Colorado River. The presence of a fossil *Cyprinodon* in the region suggests that the connection was an early one, possibly Late Pliocene or Early Pleistocene. If this is true, one would now hardly expect to find anything more than merely suggestive physiographic evidence that a connecting river or river-lake series once existed. The marked distinctiveness of the Recent fish fauna of the Death Valley system from that of surrounding systems also is in harmony with the view that the drainage has been isolated for a long time.

[39] Miller, pp. 111–19 of ftn. 14 (1944).

EXPLANATORY REMARKS ON MAP OF PLEISTOCENE HYDROGRAPHY

The lakes shown on Figure 1 include a number, particularly in southeastern California, that are both pre-Pluvial and post-Pluvial. Lakes Manly, Pahrump, Tecopa, Ward, and Amboy are regarded as pre-Pluvial bodies of water, whereas Lake Cahuilla is of post-Pluvial or Recent age. None of the lakes is believed to be earlier than Pleistocene.

An attempt has been made to trace original sources of information on these waters. The Quaternary lakes as mapped by Russell[40] are shown on later maps by Gilbert,[41] O. E. Meinzer,[42] and W. O. Clark and C. W. Riddell.[43] Meinzer's 1922 map of Pleistocene lakes[44] is the basis of subsequent charts, including the latest map by T. B. Nolan.[45]

All Pleistocene waters are not included, as several mountain lakes were, no doubt, already in existence at that time. Most *playas* probably contained at least shallow and semipermanent lakes. Lakes formed by the desiccation and fragmentation of the larger lakes (such as the separation of Lake Searles, No. 7, into two bodies at a later stage—see text) are omitted. Moreover, not all the lakes shown were contemporaneous, although that impression is given by the map. Hence the picture is greatly simpli-

[40] Ftn. 3, Pl. 1.

[41] Ftn. 2, Pl. 2.

[42] "Geology and Water Resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada," *U.S. Geol. Surv. Water-Supply Paper 423* (1917), Fig. 1.

[43] "Exploratory Drilling for Water and Use of Ground Water for Irrigation in Steptoe Valley, Nevada," *U.S. Geol. Surv. Water-Supply Paper 467* (1920), Pl. 3.

[44] Ftn. 4.

[45] "The Basin and Range Province in Utah, Nevada, and California," *U.S. Geol. Surv. Prof. Paper 197-D* (1943), Fig. 11.

fied. Only the major, now disrupted, rivers are mentioned. Others, however, are indicated on the map, following the courses of the Recent streams and definite dry canyons, except where there is contrary geological evidence.

The source of information, from which the outline of each lake named on the map was drawn, is indicated on the facing page. The boundary line of the Death Valley system was compiled largely from the excellent work by Thompson.[46]

[46] Pl. 7 in ftn. 33.

ACKNOWLEDGMENTS.—I wish to express my deep gratitude to three eminent students of desert physiography who kindly gave me the benefit of their knowledge of this former drainage. Dr. Eliot Blackwelder, Mr. Hoyt S. Gale, and Dr. Levi F. Noble were all interviewed and freely offered much helpful advice. Mr. Gale provided an original sketch showing the outlet of Lake Thompson (Fig. 1, No. 19). Financial assistance was received by a research grant from the Horace H. Rackham School of Graduate Studies, University of Michigan. Dr. Carl L. Hubbs made valuable suggestions and read the manuscript. Norman J. Wilimovsky, a student at the University of Michigan, traced the maps.

SPURIOUS LEVELS OF LAKE BONNEVILLE

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ABSTRACT

Investigation of reports of very high shorelines in the Bonneville Basin discloses that no investigated "shoreline" more than 90 feet above the Bonneville level can be attributed to the ancient lake. Checking of evidence upon which these reports were based indicates that a number of confusions and illusions, here described, are responsible.

INTRODUCTION

During a stay of nearly four years in the Utah desert area, numerous high "shorelines" of Lake Bonneville were reported to, or seen by, the writer. Rather thorough investigation of these reported or apparent high shorelines disclosed that there were a large number of shoreline segments, tufa deposits, abandoned beaches, and wave-washed surfaces between the main Bonneville level and about 90 feet above it, but no shore structures reasonably attributable to Lake Bonneville higher than that.

Although a small percentage of the high "shoreline" reports would do credit to the late Baron Munchausen, most of them were undeniably honest and were due to errors of interpretation or observation.

Most of the high "shoreline" reports, it should be noted, are not due to ignorance or stupidity on the part of the observer but are the result of "carrying over" discriminatory habits, of proved merit in most areas, into a region of markedly different observing conditions. Of these observational difficulties, G. K. Gilbert[1] was apparently well aware. In consequence, his report on Lake Bonneville, published in 1890, is still the best general work on ancient lake structures in this area.

[1] *Lake Bonneville* ("U.S. Geol. Surv. Mono.," No. 1) (Washington, 1890).

CONFUSION OF EVIDENCE

Confusion of glacial, nivation, stream, and sheetflood deposits with lake-shore features is common in this area, particularly as these deposits, in many places, merge with lake deposits.

A typical example is the "shoreline" on the southwest side of Deseret Peak (Tooele County), in the Stansbury Range. Here, at an elevation of about 8,000 feet, parts of a long level terrace are covered with boulders, so that the area resembles somewhat an ancient boulder beach, such as the Provo beach on the Stansbury Peninsula, only 30 miles away.

Study of the area indicates that the terrace on the peak is due to structural and stratigraphic control and that the boulders are remnants of the moraine of a small extinct glacier which once occupied a cirque on the southwest slope of the peak.

Confusion of meander and flood deposits with lake-shore debris is quite common; and spurious "shorelines" and "boulder beaches" can be found in the canyons of the Logan, Ogden, Weber, and Provo rivers at several locations. In Big Cottonwood Canyon, near Sandy, Utah, the mixture of lake-shore, stream, and glacial-outwash deposits with weathered fault breccia and disintegrating tillite is so complex as to make certain classification impossible.

In the upper reaches of the Sevier River are a number of old lake beds and deltas, locally attributed to Lake Bonneville. That these are lake features is undeniable; but their hydrographic isolation from the ancient lake, their small areal extent, and their elevation all suggest that they are local features. Field evidence indicates that these deltas and the dividing line between sheetflood stripping and wave-washing is almost impossible to locate *from local evidence alone.* It is also apparent, in some of these areas, such as the south end of Skull Valley, that some of the materials now forming old boulder beaches reached their approximate present locations by flood, rather than wave, transportation.

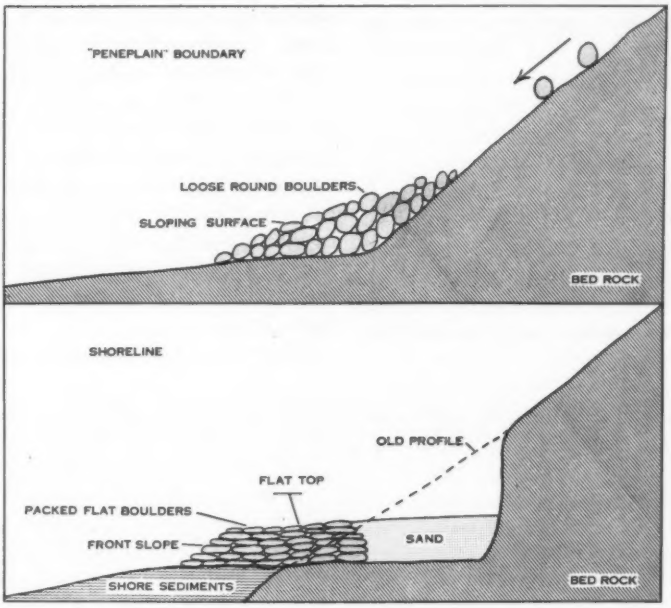

FIG. 1.—Section of a "peneplain" boundary (*upper*) and of a shoreline (*lower*), showing differences in superficial and underlying structure.

other deposits were made in ephemeral lakes or in cutoff meanders. Local causes of deposition are beaver dams, cloudburst dams, fault scarps, and overflowing of natural levees.

Confusion of old wave-washed surfaces with those stripped by sheetflooding is also easy. In some areas, where pediments extend downward into the old lake basin and shorelines are not well developed (as in parts of the Sevier Basin),

Similarity of the boulder deposits in this area, whatever their origin, is notable, particularly in the case of the older deposits, where wind action, desert weathering, and partial burial have modified not only the apparent shape of the deposit but the shapes of the original components.

A number of the reports of high "shorelines" in the Bonneville Basin owe their origin to topographic misinterpreta-

tions, such as the classification of an old erosion surface as a wave-washed surface and of the edge of such a surface as a shoreline. A good example of a pedimental boundary that closely resembles a shoreline is found on the east side of the Stansbury Range (Tooele County), just south of Johnson Pass. Here, a relatively flat shelf extends southward from the pass for about 3 miles. At the upslope margin of the shelf, where the gradient steepens to the mountain slope, are scattered clumps of boulders, faintly resembling an ancient eroded boulder beach. Although this shelf, as a whole, could hardly be mistaken for an ancient shore surface, short sections of it, taken alone, closely resemble poorly developed sections of undeniable shorelines.

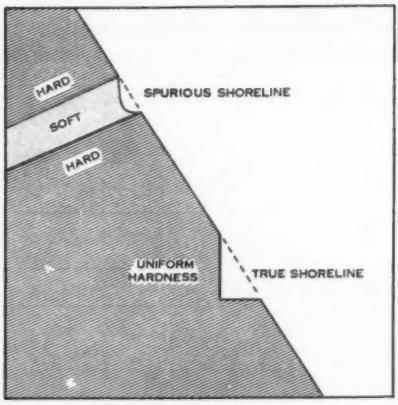

FIG. 2.—Erosion of soft stratum to produce spurious shoreline.

Sections of a so-called "peneplain boundary" and of a shoreline are shown in Figure 1. Although there is a marked superficial resemblance between the two features, they can hardly be confused if carefully studied, even though a considerable part of the evidence has been removed by erosion or buried by sheetflood deposits.

Where relatively flat-lying strata are

FIG. 3.—The slanting "shoreline" on Simpson Butte, as seen from the air. The true shoreline, of Provo age (*below*), cuts across the local stratification. The spurious shoreline (*above*) exactly parallels the stratification.

exposed in steep slopes in the lake area, softer members of the formation are weathered out, producing shelves which in many instances are reported as shorelines. As some of these cross the actual shorelines, confusion of levels is not only understandable but sometimes very difficult to eliminate.

Differences between the shape of a spurious shoreline due to rock structure and that of a true shoreline are shown diagrammatically in Figure 2. An additional criterion is that no erosional ledge above the ancient lake level is likely to have extensive tufa deposits upon it.

One of the most commonly reported spurious shorelines is the "slanting shoreline" on Simpson Butte (Tooele County). An aerial view of this feature, lighted to emphasize its stratigraphic nature, comprises Figure 3. In this area, whenever a reported shoreline roughly parallels local stratification, particularly if it is inclined or warped, repeated checking is desirable before a lacustral classification is applied.

Several "warped shorelines" in the Cedar Mountains are actually the steep faces of sills, from above which the softer limestone has eroded away.

Confusion of tufa, flowstone, caliche, and sinter leads to many erroneous shoreline reports. Fresh-water tufa deposits and sinter can be distinguished by the contained diatom skeletons. Base-exchange tufa (characteristic of highly saline water), flowstone, and caliche contain few to no diatoms. Chemical tests, in many instances, are necessary to distinguish between base-exchange tufa, flowstone, and caliche.

OBSERVATIONAL DIFFICULTIES

The ancient bed of Lake Bonneville, now a desert, in some places entirely devoid of vegetative cover, is subject to extreme development of mirages, looming, and a "paper-doll' duplication of images, owing to aerial stratification.[2] These optical effects lead to the appearance of spurious shorelines, at certain times of day only, of sufficient clarity to deceive most observers. For reasons not clearly understood, these mirage effects are much more convincing in visual observation than in photographs, although the familiar "water mirage" can be photographed successfully if the exposure is relatively long.

In general, whenever there is a thermal discontinuity in the atmosphere (an inversion is the best known but *not* the only type), there is also an optical discontinuity, the magnitudes of the two phenomena being roughly comparable. Effects of some of these discontinuities are shown in Figure 4. At the top is shown the silhouette of a mountain when the thermal gradient is normal—a condition occurring at night, on cloudy days, and for a short period in the morning. At the center is the appearance of the same mountain when there is a thermal discontinuity close to, or intersecting, the line of sight. This leads to reports of a spurious shoreline on the mountain. At times, the upper part of the view is enlarged, so that the upper part of the mountain overhangs the lower, in which case the optical effect is obvious. At the bottom of Figure 4 is shown the appearance of the same mountain when the line of sight passes through stratified air. Multiple "cutouts" and duplications are common under these conditions.

Elimination of misobservations due to atmospheric optical effects is difficult if only a short time is spent in the area. Repeated observations, at different times of day, or from different viewpoints will usually eliminate these troubles. In

[2] R. L. Ives, "Mirages in the Salt Lake Desert" (in preparation).

most instances, if the position of a distant feature remains constant when it is viewed successively through a polaroid screen, a red filter (Wratten A), and a yellow filter (Wratten K2), it is almost certainly real; but if it either vanishes or changes position as the viewing filter is changed, it is probably spurious and due to mirage effects.

In high altitudes, where the air is quite clear, as is the prevalent condition through much of the year in the Salt Lake Desert, the distance between an observer and a topographic feature can be estimated only with great difficulty. Under certain conditions, not at all uncommon in this area, two hills—one 10 miles from the observer, and the other 30—appear adjacent. As a natural consequence, the shorelines on a near-by hill

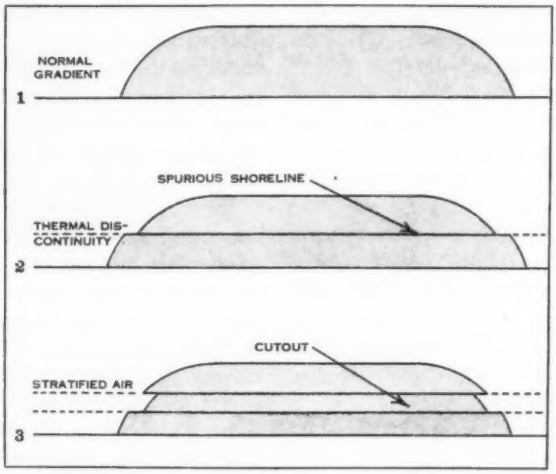

FIG. 4.—Relation of thermal and optical effects to apparent, but spurious, shorelines. *Top*, silhouette of mountain when thermal gradient is normal; *center*, spurious shoreline effect due to thermal discontinuity near line of sight; *bottom*, "cutout" produced by air stratification.

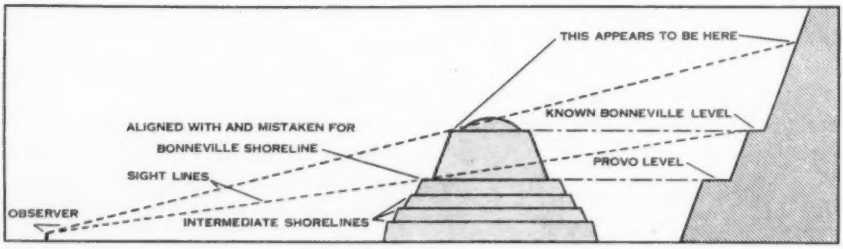

FIG. 5.—Conditions leading to the report of a spurious high shoreline, owing to lack of aerial perspective

may be incorrectly "lined up" with the known features of a more distant mountain range, with the result that a "shoreline" sector, some distance above the Bonneville, is reported on the distant range.

A sketch showing the general conditions leading to a high "shoreline" report when aerial perspective is lacking comprises Figure 5. Although field work, usually involving many miles of travel, is the only method of determining the accuracy of such a report, erroneous observations of this type may be very greatly reduced in number by use of a blue viewing filter, which increases aerial perspective.

CONCLUSIONS

Investigation of high "shoreline" reports from the Salt Lake Desert discloses that no true shorelines more than 90 feet above the Bonneville level can be attributed to the ancient lake; that most of the reports of higher shorelines are honest but mistaken; and that, until improved methods of observation are more widely adopted, reports of high shorelines may be expected to continue.

ACKNOWLEDGMENTS.—The writer is indebted to Colonel John R. Burns for transportation used in checking many of the high "shoreline" reports and to Dr. Carey Croneis for helpful discussions of observing problems and a critical reading of this manuscript.

NOTE ON RECORDING THE ATTITUDE OF STRUCTURAL PLANES

A communication received from Dr. J. A. Broggi, director of the Instituto Geologico del Peru, advocates the desirability of recording the attitude of any structural plane in terms of two numbers, the first giving the azimuth (bearing measured clockwise from true north) of the direction of the dip, and the second its inclination. Thus 40°–25° defines a plane dipping 25° to N. 40° E. (strike is thus N. 50° W.), while 220°–25° defines a plane dipping 25° to S. 40° W. (strike is N. 50° W.). While strike is actually measured in the field in many cases, this is easily converted to direction of dip by taking the strike as an azimuth reading and then adding or subtracting 90°. The latter could be avoided by using a specially graduated dial compass; i.e., one that would read the direction of dip when it was held in the position of the strike. Dr. Broggi advocates this method to simplify notetaking in the field.

REVIEWS

Volcanoes as Landscape Forms. By C. A. Cotton. Christchurch, London: Whitcombe & Tombs Ltd., 1944. Pp. 401; figs. 223. 32*s.* 6*d.*

In the field of geomorphology no name is more widely and properly renowned than that of Professor Cotton. His penetrating analyses of land forms are written in lucid style and attractively illustrated by well-chosen photographs and clean-cut sketches. There is no doubt, therefore, that this, his latest book, will be welcomed by geologists and geographers alike —more than that, being couched in readable form and burdened with few technical terms, it will appeal to any nonspecialist interested in the development of landscapes. Not all forms carved from volcanic rocks are considered; indeed, those produced in late postvolcanic cycles of erosion are omitted from discussion. In brief, focus is centered on volcanic forms little, if at all, modified by denudation.

The book runs to 401 pages, of which the first 69 deal with the mechanism of volcanism, while the rest are devoted almost wholly to morphology. No book of the kind has ever been written before; hence, as the Preface says, "the arrangement is experimental and tentative." Clearly it was this problem and the vexing business of terminology that gave the author his greatest difficulties. Alas, it must be added that his issue from these afflictions was not entirely happy. Before a sculptor starts to chisel, he should know his medium; just so, the reader should know the stuff of which volcanoes are formed before passing on to consider the resultant forms. After summarizing the mechanism of volcanic action, it might have been better, therefore, to describe in detail the products of volcanoes before proceeding to problems of morphology. With that in mind, much of the data presented in later chapters might have been presented earlier, e.g., the pages dealing with lava types and those concerned with such deposits as volcanic mudflows and welded tuffs.

The opening chapter, on "Types of Eruption," might profitably have been expanded. While the time-honored classification into Hawaiian, Strombolian, Vulcanian, etc., types is adopted, its shortcomings are properly mentioned. Neither here nor elsewhere in the book is the treatment dogmatic. Some may feel, however, that too much emphasis is laid on the chemical composition of the magma in determining the type of activity, and too little on the temperature, gas content, degree of crystallization and depth of the magma chamber. Incidentally, the term "Plinian eruption" has been used in such widely different senses by various writers that it has come to have little meaning other than to signify catastrophic explosion following a long period of quiescence. It would seem wise, however, to exclude from the category all "ultra-Vulcanian" eruptions in which only old, lithic debris is expelled, for the eruption which Pliny described involved mainly the discharge of fresh magma as pumice and scoria from the feeding chamber of Vesuvius.

In chapters ii and iv, on "Lava Volcanoes," an excellent account is given of the Hawaiian type of activity, based mainly on the lifelong studies by Jaggar. It is welcome to see full recognition made of the extremely complex feeding mechanism of Hawaiian volcanoes, of the importance of rifting, and of the subterranean pulsing of magma that continually makes Hawaiian volcanoes tumesce and subside as if they breathe. Welcome, also, is the introduction of Jaggar's terms "pyromagma" for the free-flowing, often foaming, lighter magma that grades downward into the relatively immobile "hypomagma," with its gas chiefly or wholly in solution; and the usage of "bench magma" and of "epimagma" for the degassed, inflated pyromagma. Without recognition of these various forms, the mechanism of Hawaiian volcanoes cannot rightly be understood.

Chapter iii includes a résumé of ideas developed at the Kilauean lava lake by Jaggar, Day, Shepherd, and others relative to the heating of lava by reactions between escaping gases and by the combustion that attends engulfment of the walls of the lake. Some may question whether heat derived by such processes is enough to offset the cooling caused by gas expansion. Perhaps too much insistence has been placed on the observations at Kilauea; for the conditions that obtain in an open lava lake with strong convective circulation are very different from those that prevail in most of the active

volcanoes of the world. It may also be that the importance of gas-fluxing in reopening volcanic conduits after periods of dormancy has been overemphasized. One wonders whether or not, in a work devoted primarily to landscapes, such debatable topics merit more than passing mention.

Chapter v deals with "Pumice Volcanoes"; but the heading, like several others in the book, is misleading, for here Professor Cotton includes discussion of the temperature and source of magmas and the origin of magmatic gases, and he is concerned not merely with volcanoes that erupt pumice, as that term is generally understood, but with explosive volcanoes in general. In reference to the temperatures of the more siliceous lavas the suggestion is made that the presence of tridymite and cristobalite among the final products of crystallization may indicate temperatures in the vicinity of 1,500° C. and that some such temperature may be required to make these siliceous lavas flow freely! True, reference is added in a footnote to low-temperature "pneumatolytic" cristobalite, but the idea that a siliceous lava could perhaps approach complete solidification at temperatures approximating 1,500° C. is quite erroneous. Temperatures between 600° and 900° C. are normal for siliceous flows. Many other questions jump to mind in reading this chapter. Does the effervescence of a magma tend to raise its temperature? How important is the content of ferrous iron in controlling the viscosity and determining thereby the type of discharge? Is it as critical as temperature or the vapor pressure of the still-liquid fraction of the magma about to escape?

Discussion of the source of magmas is brief and based chiefly on the latest opinions. Unfortunately, or so it seems to the reviewer, most space is given to Van Bemmelen's conception that "volcanic activity on the top of orogenic uplifts is caused by palingenetic, hybridic, or syntectic magmas. These magmas are saturated with emanations and this explains the high explosiveness." Perhaps granite batholiths do originate by metasomatic alteration of the roots of mountains, but to relate "granitization" to volcanism is to overtax credulity. Most batholiths consist of granite, and most volcanoes, even in orogenic belts, erupt basalt; and these facts alone should give cause to doubt an intimate connection between them. Moreover, the geological record shows that submarine discharge of pillow basalt and injection of serpentine usually precede orogeny, that batholithic invasion mainly follows folding and causes mountain-uplift, and that most volcanism begins at a much later date. The view of Kennedy and Anderson, referred to by Professor Cotton, that batholiths originate at the expense of the sial and that volcanoes are fed from underlying layers of tholeiitic and olivine basalt seems deserving of much wider recognition. The ensuing pages, dealing with revival of activity after dormancy, by gas-fluxing of plugs and by retrograde boiling of magma, present a summary of the ideas of Morey and Rittmann.

Chapter vi, devoted principally to Vesuvius and its cycle of activity, embodies a clear account of the theories of Perret and Rittmann. So many complex factors determine the types of volcanic eruption, and a single volcano emitting magma of uniform composition may behave in such a bewildering variety of ways, that one hesitates to accept the suggestion that differences between the behavior of Hawaiian and Vesuvian volcanoes may be related to minor differences in the chemical composition of their magmas.

Part II, the main portion of the book, is an extremely able study of volcanic landscapes, and it shows that the author has kept closely in touch with recent literature. It begins with an account of "Domes and Cones of Basaltic Lava." Characteristic of domes are the broad and gently sloping volcanoes of Hawaii, often referred to by others as "shield volcanoes." Their inner structure and mode of growth are clearly explained. Most of them are shaped like overturned spoons or canoes, in contrast to the steeper basaltic cones (shields) of Iceland, the outlines of which are approximately circular, since they grow entirely by overflow from the summit vents and are not augmented, like the volcanoes of Hawaii, by repeated discharge from fissures on the flanks.

The next three chapters are mainly concerned with basaltic lava plateaus, the surface features of basaltic flows, and the fragmental ejecta of basaltic volcanoes. These forms are then contrasted with those developed by eruption of viscous and more siliceous lavas that pile over the vents as steep-sided cumulo domes or tholoids, like that capping Mont Pelé, or are forced upward, piston-like, to produce plug domes, such as Lassen Peak.

Particularly good is the chapter describing "Ash Showers and *nuées ardentes*." For the first time in any textbook, one finds full dis-

cussion of the various kinds of *nuées*, not only those such as were discharged by Mont Pelé and the Soufrière of St. Vincent and those produced by the crumbling of domes, as in Java, but also those erupted from swarms of fissures, as near Katmai in 1912. Professor Cotton's insistence on such fissure eruptions of pyroclastic ejecta is not surprising when one recalls that in the North Island of New Zealand welded tuffs cover approximately 10,000 square miles, locally to depths of several hundreds of feet. Doubtless many other extensive rhyolitic plateaus, long thought to consist of lava flows, will prove, on further examination, to be made of similar, fissure-erupted tuffs. The author's experience in New Zealand has also led him to stress a fact not often noted, namely, that some of the most violent explosive eruptions from central vents fail to produce large cones but instead leave widespread blankets of pumice and ash. Two possible causes of such "coneless showers" are mentioned; a third may be added, namely, a shallow explosion focus which tends to give wide scatter to the ejecta.

Very likely, the most voluminous explosive eruption of historic times was that of Tamboro, on the Island of Sumbawa, in 1815. Verbeek's estimate that no less than 150 cu. km. of material were discharged has been handed down from one text to another ever since, though as Van Rheden has demonstrated, the estimate is approximately five times too large. Indeed, it seems safe to say that within historic times no volcano has discharged more than 50 cu. km. of material in a single explosive cycle.

The next chapter, on "Ash-built and Stratified Cones" is another unusually good discussion, rich in up-to-date material. Reference is made, for instance, to a feature too little realized, namely, the phenomenally rapid growth possible in ash cones and pumice cones. In 1937, the cone of Vulcan, in New Britain, rose to a height of 600 feet during its first day; within three or four days it was 742 feet high. The Mexican volcano Paricutin rose to 1,100 feet in the first ten weeks. Here, also, one finds well-merited space given to another topic generally slighted, namely, "volcanic mudflows." Especially in tropical regions and among snow- and ice-capped cones, the mingling of loose ejecta with water produces slurries of mud, heavily charged with boulders, that spread for vast distances; and many of the coarse deposits found in ancient volcanic regions are clearly of this origin. Professor Cotton, aware that "mudflow" is a misnomer as applied to such materials, has had the courage to introduce an alternative term long familiar to volcanologists, the Javanese word "lahar." Doubtless, some will raise objections, as others did to the Hawaiian names "aa" and "pahoehoe," but this reviewer hopes that "lahar" has come to stay and will gain a wide acceptance.

In describing "Maars and Tuff Rings," a brand-new word, "ubehebe," is invented for volcanic embryos or "maars" devoid of water. The name comes from the Ubehebe craters in Death Valley, a series of at least five (not two) basins produced by explosions of basaltic scoria mixed with sedimentary debris. It seems adequate, however, to call such depressions, bordered by low rims of fragmental ejecta, simply "explosion pits."

Space is also allotted to descriptions of meteor craters and to cryptovolcanoes, like the Steinheim Basin and the Rieskessel of Germany and the ring structures lately studied in this country by Bucher.

Following a brief account of submarine eruptions and pillow lavas comes the longest chapter in the book, devoted to "Craters and Calderas; Volcanic Depressions and Lakes." Here, again, is a wealth of up-to-date information. Collapse, rather than explosive decapitation, of cones is properly considered as the prime cause of calderas, engulfment resulting chiefly from hurried drainage of magma from beneath the tops of volcanoes either by colossal discharge of ash and pumice, as at Krakatoa, Crater Lake, and Monte Somma; by rapid outflow of fluid lava from the lower flanks, as in Hawaiian volcanoes; or by subterranean migration of magma. Van Bemmelen's view that formidable arcuate rents have developed on Javanese volcanoes by downsliding of portions of overloaded cones resting on a weak, inclined floor is described; and the manner in which sectors of cones may collapse to form eccentric depressions like the Val del Bove on Etna is noted. Especially noteworthy are the pages discussing the largest volcanic depressions of all (now, for the first time, finding place in a general text), namely, volcano-tectonic depressions. These form by downbending and faulting along tectonic lines following tremendous outwellings of rhyolitic ash from swarms of fissures. In other words, they are related to great sheets of welded tuff (ignimbrite), like those along the Barisan Rift of Sumatra and in the North Island of New Zealand. A particular example is

the basin, 100 km. long and 31 km. across, that holds Lake Toba.

The book ends with treatment of the erosion of volcanic landscapes, first telling of the denudation of basalt and ignimbrite plateaus and of basaltic plains, both by rivers and glaciers, and concluding with an account of the destruction of volcanic mountains and the erosion cycle as applied to calderas. Knowing Professor Cotton's unusual skill in analyzing stages of erosion, one would have been glad to see this discussion carried further.

The book is effectively illustrated by 138 line-drawings and 85 photographs. Fifteen of the latter are excellent aerial views that whet the appetite for more. Great care has been exercised in preparing the Index, and the proofreading throughout has been done so thoroughly that a misprint is as hard to find as a needle in a haystack. Oddly enough, the only slips noted occur together in the caption under Figure 186, where steptoes surrounded by basaltic lava are said to be composed of granitic terrain, though they are really islands of basaltic scoria, and the locality is not in Washington but in Oregon.

If anyone wishes to gain a comprehensive and balanced picture of current views concerning volcanoes, this is the book for him. Few will gainsay that it is by far the best general discussion of volcanoes that has yet appeared in English in textbook form.

HOWEL WILLIAMS

Tectonic Map of the United States. Prepared under the direction of the COMMITTEE ON TECTONICS, DIVISION OF GEOLOGY AND GEOGRAPHY, NATIONAL RESEARCH COUNCIL, CHESTER R. LONGWELL, Chairman. Tulsa, Okla.: American Association of Petroleum Geologists, 1944. Scale 1:2,500,000, or 1 inch = 40 miles. Printed in 7 colors, on 2 sheets; full map, size about 80 × 50 inches. $2.00 rolled in mailing tube; $1.75 folded in manila envelope; $1.50 in lots of 25 or more, rolled or folded.

The much-needed, long-desired tectonic map of the United States has at last appeared. Conceived at the initial meeting of the Committee on Tectonics in 1922, the project passed through a slow period of gestation, during which ideas and plans took shape. Active assembling of the data began in 1934, when the country was divided into eleven "tectonic districts" and each member of the committee assumed responsibility for one district. Later, the number was increased to fourteen, including one in southeastern Ontario. Added also were adjacent parts of Mexico for which abundant data were available.

A full explanatory statement of the development of the project, the techniques for delineating the various structures, the representation in color of kinds and ages of bedrock in certain large areal units, together with other pertinent information, has recently appeared in the *Bulletin of the American Association of Petroleum Geologists*, Vol. XXVIII (1944), pp. 1767–74, under the title "Tectonic Map of the United States," by Chester R. Longwell.

The material compiled by the members of the committee was co-ordinated and prepared for drafting by Philip B. King, vice-chairman of the committee, to whom much credit is due for the final consummation of the map. Early in 1940 about two hundred lithoprinted copies of a preliminary black-and-white edition of the map, drafted under the direction of G. W. Stose, of the United States Geological Survey, were distributed to organizations and individuals throughout the country, with requests for corrections of errors, suggestions of desirable changes, and additional data. Benefiting from this careful scrutiny, the completed map should now represent the structural features of the United States and some adjoining areas about as authoritatively as is possible with present knowledge.

The scale being identical with that of the *Geological Map of the United States* issued by the United States Geological Survey in 1932, the two maps can readily be used to supplement each other. The manifold different structures are clearly and effectively depicted, making the new map extremely useful for structural studies of all sorts, and especially those of broad regional scope.

R. T. C.

UNITED STATES GEOLOGICAL SURVEY STAFF CHANGES ANNOUNCED

Director W. E. Wrather, of the United States Geological Survey, has announced recent organizational changes within the Geologic Branch of the Survey, which is headed by Chief Geologist W. H. Bradley.

The Geologic Branch has been subdivided into two divisions and a technical service and administrative group. Dr. H. M. Bannerman has been named chief of the Division of Economic Geology. During most of the war period he served as chief of the Section of Nonmetallic Minerals.

Dr. H. S. Ladd has been designated chief of the Division of Areal Geology and Basic Sciences. He was formerly regional geologist, in charge of the Rolla, Missouri, office of the Survey. Dr. J. W. Peoples, assistant chief geologist, has been named head of the Technical and Administrative Group.

A special research staff has been set up within the Geologic Branch, having advisory functions in connection with long-range research planning and Branch policies. This staff includes Drs. D. F. Hewett, G. F. Loughlin, and W. W. Rubey. Other geologists are temporarily assigned to this staff as the planning needs dictate.

A new Section of Geologic Information and Reports has been established. Don L. Carroll, until recently foreign editor and staff geologist of the *Oil Weekly*, has been designated chief of the new section.

The following sections now comprise the Division of Economic Geology:

Geology of Fuels, H. D. MISER, *Chief*
Geology of Metalliferous Deposits, CHARLES F. PARK, JR., *Chief*
Geology of Nonmetalliferous Deposits, JOSIAH BRIDGE, *Acting Chief*
Foreign Geology, J. V. N. DORR, II, *Acting Chief*

Within the Division of Areal Geology and Basic Sciences are included the following sections:

Areal Geology, J. T. HACK, *Acting Chief*
Engineering Geology, E. C. ECKEL, *Chief*
Chemistry and Physics, W. T. SCHALLER, *Chief*
Paleontology and Stratigraphy, J. B. REESIDE, JR., *Chief*
Petrology, C. S. ROSS, *Chief*
Military Geology, E. S. LARSEN, III, *Acting Chief*
Geophysics, J. R. BALSLEY, *Acting Chief*

The Technical Service and Administrative Group includes the following units:

Manuscript Review Board, C. H. DANE, *Chairman*
Geologic Map Editor, E. N. GODDARD
Geologic Cartography, L. B. PUSEY, *Chief*
Committee on Geologic Names, MISS FRANCES WILLOUGHBY, *Secretary*
Office of the Chief Clerk, MRS. A. L. BROWN, *Chief*

Changes in field assignments have also been announced. A. L. Weissenborn, of the Rolla, Missouri, office, has been designated as regional geologist at Spokane, Washington. Robert A. Laurence has been made eastern regional geologist with temporary headquarters at Jefferson City, Tennessee. Charles B. Hunt, formerly chief of the Military Geology Unit, has been designated regional geologist at Salt Lake City.